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FLIGHT TEST DIVISION

# HYDRODYNAMICS MANUAL



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**NAVAL AIR TEST CENTER**

**Patuxent River, Maryland**

## FOREWARD

The seaplane testing manual has been prepared as a practical guide for the conduct of tests of Naval seaplanes designed for partial or complete operations on the surface of the water during take-off, landing and maneuvering.

An attempt has been made to present information pertinent to the hydrodynamic testing of seaplanes. Standard instrumentation in common usage has been referred to only briefly. In order to provide a better understanding of the basic philosophy of hydrodynamic testing some background aspects of the science of hydrodynamics have been included.

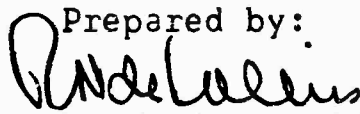
The manual does not attempt to solve all the problems that may be encountered since tests and methods of tests are continually changing. It is a beginning step and has been organized to permit ease of revision and modernization.

## ACKNOWLEDGEMENT


Acknowledgement is gratefully made to all those seen and unseen who helped in the development and preparation of this manual. The organization of much of the background material came from unedited class notes of Prof. Boris Korvin Kroukovsky of the Experimental Towing Tank, Stevens Institute of Technology, Hoboken, New Jersey. Many references other than those listed were investigated in order to present an orderly development of the subject matter.

In particular, mention is made of Miss Rhoda Thompson who made all the line drawings and Mrs Jane Rainone and Mrs Sylvia Rogers who deciphered the original manuscript and prepared it for publication.

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**CHAPTER 1**  
**INTRODUCTION**

- 1.1 Current Seaplane Designs**
- 1.2 Seaplane Types**
- 1.3 Symbols and Definitions**

## 1.1 CURRENT SEAPLANE DESIGNS

The development of seaplanes has been a slow and gradual evolution from short afterbody hulls with low performance characteristics (JRF) to current fleet-type seaplanes like the P5M-2. The evolution process has resulted in hull changes including longer afterbodies, faired-Vee steps, hydro-flaps and low chine bows. When viewed objectively, seaplane development has lagged far behind that of its landplane counterpart. A comparison of the salient characteristics between the PBM of World War II fame and the current P5M-2 will serve to illustrate the relatively small degree of improvement in the seaplane.

The reasons for the seaplanes relatively poor rate of development are varied but can essentially be attributed to the following:

- a. Lag in the development of adequate seadromes, mooring, servicing and maintenance.
- b. Lack of precise maneuvering control on water.
- c. Speed differential in favor of the landplane for same type mission.
- d. Advancement of engine reliability for long landplane over-water flight.

Despite this list of deterrents to seaplane development, there have always been strong supporters of the seaplane that have argued for its many potentialities. The high gross weights and high landing speeds of modern aircraft require runways of great strength and length. The seaplane, however, has almost unlimited runway available even in sheltered water. This makes possible operations from relatively unprepared surfaces with mobility and greatly reduced vulnerability from attack.

The advent of the turbo-prop and the turbo-jet engine has given added impetus to seaplane development. The use of turbo-prop gave excellent maneuverability with an ideal prop-reversing system. The use of jet engines has resulted in designs that employ less clearance between water surface and engine leading to a cleaner and more streamlined design. As a result of more streamline seaplane design, aerodynamic and hydrodynamic requirements could be made commensurate with each other to

a greater degree than was previously possible. It is now hydrodynamically possible to build seaplanes employing the transonic area rule for speeds greater than Mach. 1.

This manual attempts with suitable background material to show what tests are currently considered feasible for seaplanes, how the tests are performed and what these tests are designed to show. Present seaplane testing procedures are the result of a gradual refinement of qualitative seaplane testing of conventional hulls. Full scale testing, although mainly a modified extension of towing-tank technique, was developed to make the most of the useable characteristics of the full-scale article rather than to check model results.

Accrued full scale test experience resulted in standard tests for measuring seaplane performance. Small improvements in full scale performance could not always be detected by these tests. The development of Vee steps and fairings, the use of hydro-flaps and the development of the high length-beam ratio seaplane hull have all evolved from towing tank model work and tested full scale in a qualitative sense with little regard for correlation with model results. Full scale tests using the techniques of this manual have already demonstrated that the performance of high speed seaplanes can be obtained successfully from the standpoint of hydrodynamics. However, much work is yet to be done and improvements in the technique of quantitative testing are an excellent starting point.



## 1.2 SEAPLANE TYPES

Many different seaplane types have made their appearance since the early days of aviation. When the overall concept of water-based aircraft is reviewed, it appears possible to make the following arbitrary breakdown based on differences in types:

- a. Hull
  - (1) Amphibious
  - (2) Skis
  - (3) Foils
- b. Float
  - (1) Amphibious
- c. Displacement Body
  - (1) Skis
  - (2) Foils

The hull type seaplane is designed to incorporate both displacement and planing characteristics in one structure.

Hull types may be described by the general term High-length beam ratio or low-length beam ratio. The step of the hull type seaplane is a discontinuity of the hull lines and the primary function of the step is to break up and reduce suction on the afterbody. Seaplane hulls may have different types of steps, and be further classified by step planforms as follows:

- a. Transverse
- b. Vee
- c. Faired Vee
- d. Pointed

Depending on the combination of forebody-afterbody and step, the seaplane hull may be described as:

- a. Short afterbody

- b. Long afterbody
- c. Extended afterbody
- d. Planing tail

Since one of the major features of the seaplane hull is the shape of the hull bottom, further classification may be made on the basis of shape:

- a. Straight Vee
- b. Concave Vee
- c. Scolloped Vee
- d. Rounded or constant force bottom

The hull provides both the buoyant force during low speed and the dynamic force during high speed. In the generation of dynamic lift, most hulls require some type of spray control. This control is generally accomplished by spray rails externally mounted which control the flow and reduce any adverse suction which might increase resistance. Chine flare and deadrise variation can also be used to control spray. Lateral stability in the displacement range is achieved by the use of wing tip floats. Older hull type seaplanes have used sponsons and stub wings for lateral stability. The hull form is particularly adaptable for the incorporation of amphibious capabilities. Landing gear can be mounted to retract into the hull, thereby increasing the versatility of the seaplane to the extent that operations are also possible from runways. Amphibious vehicles have, in the past, not been too successful because of the heavy weight penalty of the landing gear and the resulting "beef up" of the carry-through structure. Recently, some seaplanes have incorporated a wheel system similar in operation to landing gear but designed solely to permit egress from the water via ramp. Skis and foils designed to generate dynamic lift in the planing regime can also be attached to hull type seaplanes. They can be flush mounted such that when the ski or foil is retracted the hull bottom retains the normal contour or they can be mounted with any degree of protrusion. Skis and foils are covered in detail in section 4.10.

Float type seaplanes are similar in construction and principle to the hull type seaplanes except that the float may be either single or twin, and in either case the length

beam ratio is usually higher. In the case of the single main float, transverse stability is accomplished by the use of wing tip floats. In the past, there have been amphibious versions of single float type seaplanes and several modern commercial twin float seaplanes possessing amphibious capabilities by incorporating wheels which retract into the float.

Seaplanes whose dynamic lift is provided by either foils or skis, or a combination of both require only a simple shape with which to provide the necessary static or buoyant displacement. A true displacement body is sometimes difficult to obtain since some type of water flow guidance system is usually necessary prior to the seaplane entering the planing range. A flow guidance system consists of spray rails which guide the flow and prevent excess suction on the displacement body. The XF2Y, with both single and twin ski arrangements, required that the afterbody sustain a certain amount of dynamic pressure and consequently the afterbody was designed to resist waterflow and generate lift even though the hull was basically a displacement body.

### 1.3 SYMBOLS AND DEFINITIONS

In the study of seaplanes there is a continual need to refer to certain portions and properties of hulls and floats which are not defined in common terminology. Many definitions have been carried over from Naval architecture; some new words have been introduced to describe unique features of seaplanes and many common words have been given specialized meaning. A list of the various terms used in connection with seaplanes is presented below. Certain of the terms are defined graphically in figure 1:1.

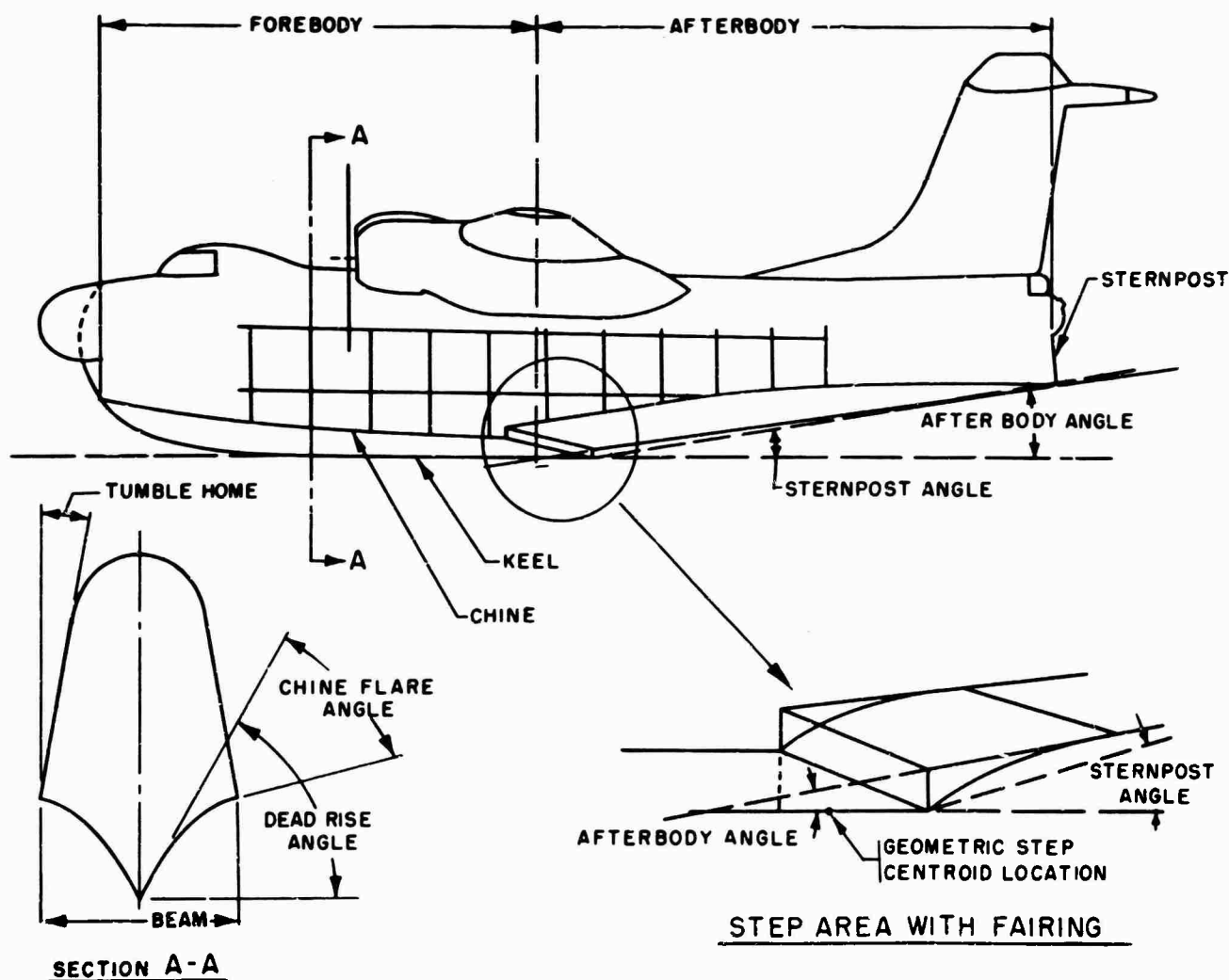


Figure 1:1

Afterbody - That part of a seaplane hull or float aft of the main step and terminating at the sternpost.

Afterbody Keel Angle - The angle between the tangent to the forebody keel at the step and the straight portion of the afterbody keel.

**Angle of Chine Flare** - The angle between the tangent to the chine flare at the chine and the transverse axis of the seaplane hull or float.

**Angle of Deadrise** - The angle formed in the transverse plane by the intersection of a horizontal plane perpendicular to the transverse plane and a line joining the keel and chine. The angle may be variable or constant. If the angle is variable, the point at which the deadrise angle is defined is called the local deadrise angle.

**Angle of Heel** - The angle between a horizontal plane and the lateral axis of the seaplane on the water.

**Base or Keel Line** - A longitudinal line usually extending forward from the straight position of the keel from which the seaplanes vertical dimensions are referred.

**Beam** - The width of the seaplane float or hull at the chines. Usually specified as the maximum for the entire hull length or the width at the step.

**Blister** - A thin continuous sheet of water not yet separated into drops raised by the motion of a hull or float and separated from the free-water surface by an air space.

**Bon Jean Curve** - A set of scaled lines on a side elevation representing the area below the curve as equal to the volume of the hull below the curve.

**Buttock Line** - A contoured bottom line formed by the intersection of a plane parallel to the longitudinal plane of symmetry with the hull proper.

**Center-of-Buoyancy** - The center of gravity of the fluid displaced by the body.

**Chine** - The intersection of the bottom of the hull with the sides of the seaplane float or hull.

**Chine Flare** - Concave curvature of a planing surface near the chine to control spray.

**Crown** - A convex deck.

- Displacement** - The total volume or weight of water displaced by the hull or float.
- Draft** - The vertical distance from the undisturbed water surface to the lowest point on the hull or float usually on the keel at the step.
- Emergence** - A description of the process whereby a ski after being totally submerged penetrates the surface of the water and is thereafter only partially submerged. The term is used infrequently since the ski usually goes from being totally submerged to the planing state in one move and the process is therefore better described by the term unporting.
- Fetch** - Distance over which the wind has been acting on the surface of the sea.
- Float** - A completely enclosed watertight structure attached to an aircraft to give it buoyancy and stability when in contact with the water.
- Forebody** - That part of a seaplane hull or float forward of the main step.
- Freeboard** - Height of deck above the still water surface.
- Getaway Speed** - The speed at which the seaplane becomes entirely airborne. This is usually the same as the fly-off speed.
- Heave** - The vertical oscillation of a seaplane such as that which occurs during porpoising.
- Hook** - An uncontrollable turn usually at low speed near hump.
- Hump Speed** - The speed of a seaplane during take-off at which the resistance reaches a maximum.
- Hydro-flap** - A specialized type of moveable planing surface designed to provide supplementary hydrodynamic lift. Usually designated in the horizontal plane.
- Hydro-foil** - Any surface designed to obtain reaction from the water through which it moves, generally not close to a boundary.

- Hydro-ski** - A surface designed to obtain a reaction from dynamic force when operating close to a boundary.
- Keel** - The external longitudinal structural member on the centerline of the bottom of a seaplane hull or float.
- Load Water Line** - The water line at rest of a seaplane at indicated design load.
- Length/Beam Ratio** - The ratio of the sum of the forebody and afterbody lengths to the maximum beam width of a seaplane hull or float.
- Lower Trim Limit** - The lowest trim angle boundary below which low angle porpoising exists.
- Metacenter** - The point in a seaplane hull or float about which the hull or float rotates when inclined at relatively small heel angles.
- Metacentric Height** - The distance from the center of gravity to the metacenter of a floating body.
- Planing** - The movement over the water at such speeds that the majority of the vertical force is derived from the dynamic reaction of the water.
- Planing Surface** - A surface designed to obtain dynamic lift from the water over which it moves.
- Porpoising** - An undulatory movement of a seaplane consisting of a combination of a vertical oscillation and an oscillation about its transverse axis which occurs at certain stages of planing.
- Porting** - The process whereby the ski changes from a state of steady planing on the surface of the water to a state of at least partial submergence. The process is more frequently described by the term submergence.
- Pull Speed** - That speed at which the elevator is pulled sharply upward.
- Resistance** - The horizontal force opposing the motion of a seaplane hull or float from some arbitrary point of reference.

- Roach or Rooster Tail** - A heavy rising sheet of water above the undisturbed water level which exists behind the hull or float.
- Sea** - Those waves generated by the local wind and traveling nearly with the wind.
- Significant Wave Height** - Average of the heights of the upper  $\frac{1}{3}$  waves that pass a given point.
- Skeg** - A vertical fin attached to the keel at the sternpost.
- Skip** - An uncontrollable dynamic maneuver of hydrodynamic origin whereby a seaplane leaves the water after a normal landing or before a normal take-off. Usually refers to a phenomena in smooth water.
- Spray Strip** - A strip projecting from the hull of a seaplane to change the manner in which the spray is directed away from the hull.
- Sponson** - A protuberance from a seaplane hull designed to increase the beam or give lateral stability at rest.
- Step** - A break in the form of the bottom of a float or hull, designed to lessen suction effects and improve control over the longitudinal attitude.
- Sternpost** - The vertical member at the aft end of the afterbody.
- Sternpost Angle** - The angle between the line tangent to the forebody keel at the step and the line between the step and the sternpost.
- Stub Wing** - A small wing set at the waterline on both sides of a seaplane hull to provide lateral stability at rest on the water.
- Submergence** - A process similar to the reverse of unporting. That is the ski is no longer supported in its motion on the surface of the water but usually stalls and becomes wholly or partially submerged.
- Swell** - Wind-generated waves which have advanced into regions of weaker winds or calm and are decreasing in height.



Tail Extension - That portion of a seaplane hull aft of the sternpost for the support of the tail surface.

Trim Angle - The angle between the undisturbed water ahead of the seaplane and the extension of the longitudinal axis or keel line.

Trim Track - The curve of trim against speed.

Tumble Home - The inward slope of the sides of the hull above the chine.

Unporting - The process whereby a ski that is wholly or partially submerged changes from its submerged position to a position on the surface of the water and is thereafter supported by dynamic forces.

Upper Trim Limit - The highest trim angle boundary above which high angle porpoising exists.

Ventilation - The supply of air behind the main step and under the afterbody.

Warp - The variation of deadrise angle along the length of the hull.

Waterline - A line on the hull formed by a plane cut parallel to some base line.

Water Plane - The surface formed by a plane cut through the hull parallel to some base line.

Water Loop - An uncontrollable turn made while taxiing or moving at relative high speed on the water.

Wave Height - The vertical distance,  $H$ , from the trough to the crest.

Wave Length - The horizontal distance,  $L$ , from crest of one wave to the crest of a succeeding wave.

Wave Steepness - Ratio of height to the length of the wave, more commonly  $L/H$ .

In the science of hydrodynamics, certain symbols which have a wide range of applicability are defined below. Specialized symbols, used in the basic theory of pressure

distribution and impact, are not included below but are defined in the sections dealing with specialized theory.

# SYMBOLS

Beam	$b$
Deadrise	$\beta$
Yaw angle	$\psi$
Specific weight of water	$w$
Basic gross weight (Initial load on the water)	$\Delta_0$
Draft	$d$
Heel angle	$\phi$
Length - forebody	$l_f$
Length - afterbody	$l_a$
Heave	$h$
Flight path angle	$\gamma$
Trim angle	$\gamma$
Elevator deflection	$\delta_e$
Wing flap deflection	$\delta_f$
Longitudinal point of tangency of main spray	$X$
Lateral point of tangency of main spray	$Y$
Vertical point of tangency of main spray	$Z$
Getaway speed (ft/sec)	$V_G$
Landing speed (ft/sec)	$V_L$

Test gross weight

$\Delta$

Scale factor

$\lambda = L_{FS}/L_m$

Resistance

R

Characteristic length

L

Kinematic viscosity

$\nu = \mu/\rho$

Surface tension

$\sigma$

Acceleration of gravity

g

Density

$\rho$

Certain combinations of quantities are used to form dimensionless coefficients. These recur sufficiently often to list.

#### DIMENSIONLESS COEFFICIENTS

Load coefficients

$$C_{\Delta} = \frac{\Delta}{wb^3}$$

Speed coefficient (Froude No.)

$$C_v = \frac{V}{gb}$$

Heave coefficient

$$C_h = h/b$$

Resistance coefficient

$$C_R = \frac{R}{wb^3}$$

Yawing moment coefficient

$$C_{M\psi} = \frac{M\psi}{wb^4}$$

Planing coefficient

$$K = 2C_{\Delta}/C_v^2$$

Trimming moment coefficient

$$C_M = \frac{M}{wb^4}$$

Longitudinal spray coefficient

$$C_x = X/b$$

Lateral spray coefficient

$$C_y = Y/b$$

Vertical spray coefficient

$$C_z = Z/b$$

Reynolds number

$$Re = VL/\nu$$

Weber number

$$W_N = V^2 L / (\sigma / \rho)$$

## CHAPTER 2

### BASIC HYDRODYNAMICS

- 2.1 Seaplane Motions
- 2.2 Hydrostatic Forces (Displacement Range)
- 2.3 Dynamic Forces (Planing Range)
- 2.4 The Hydrodynamic Force
  - 2.4.1 The Lift Force
  - 2.4.2 Resistance and the Drag Force

## 2.1 SEAPLANE MOTIONS

To provide an understanding of the test procedures to be discussed, a brief discussion of the general forces acting on a seaplane under static and dynamic loads is presented.

The operations of seaplanes from water are distinguished by several unique problems that exist because seaplanes operate in two media - air and water. Once the seaplane has left the surface of the water, its characteristics are similar to those of other fixed wing airplanes. Therefore the determination of its airborne performance follows those procedures set down for the performance determination of comparable landplanes. The motions of seaplanes on the water, however introduce additional complications. The seaplane goes through a transition process from a state of static buoyancy (the displacement range) to dynamic planing (the planing range). Not only is the seaplane required to accomplish the transition smoothly but the seaplane must be designed to successfully encompass operations in three basic regimes i.e. waterborne buoyancy, waterborne planing and airborne flight.

In the displacement range the seaplane must be capable of withstanding upsetting moments introduced by the action of wind and wave either while moving or moored. The seaplane must also be capable of maintaining sufficient reserve buoyancy up to maximum design gross weight. In the displacement range the seaplane acts most like a boat. The watertight hull or float spaces must be designed so that for any given load on the water an acceptable static flotation trim angle will result. The static trim angle will depend on the division of watertight compartments and the resulting center of buoyancy.

In the planing range the seaplane must be capable of accelerating to take-off while maintaining stability and controllability about all three axes. The requirement for operations in both the buoyant and planing regimes places a unique restriction on the seaplane since the transition from one to the other must be smooth. As the hull speed increases from zero forward velocity there is some speed at which the resistance of the hull becomes a maximum. This point is referred to as "hump speed". This is the point at which the lift force shifts from being predominantly buoyant to being predominantly dynamic. Prior to the advent of faired-Vee steps, the transition from the displacement range to the planing range was quite distinct and was usually facilitated by the pilot pulling the yoke backward then

pushing forward. This procedure was called "getting up on the step" and corresponded to the hump speed. With improvements in step design, the pilot is no longer required to help the plane on the step and hump speed determination becomes difficult. Figure 2:1 illustrates the hump speed as the point of maximum resistance and shows the variation of resistance and thrust with the increase of speed. As a general rule, hull trim angles also become maximum in the area around hump speed.

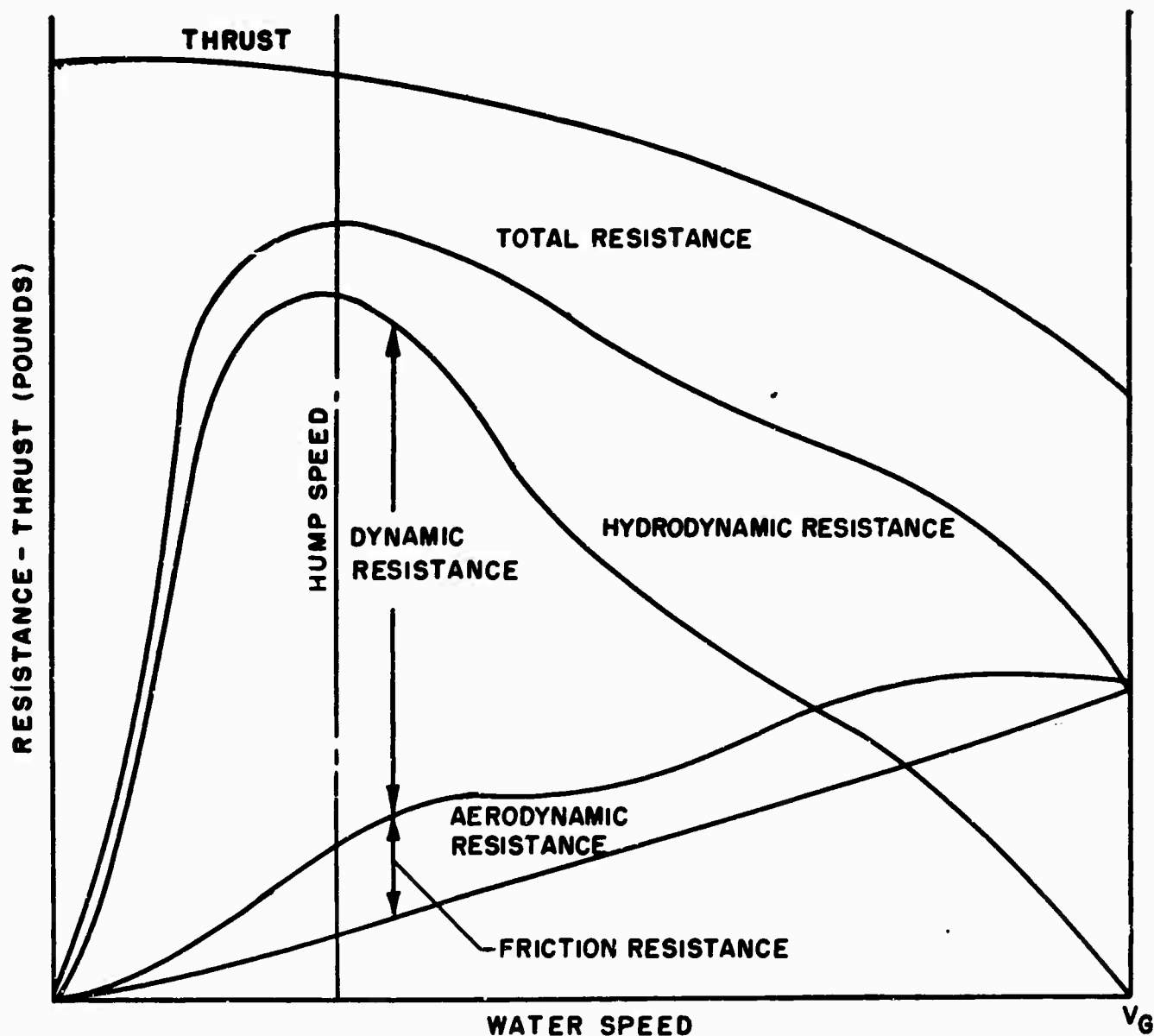


Figure 2:1

## 2.2 HYDROSTATIC FORCES - DISPLACEMENT RANGE

In the displacement range, lift is created mainly by buoyant forces. The hull is made watertight and compartmentalized to provide adequate flotation, reserve buoyance and static trim. Provisions must also be made for possible damage and subsequent flooding. Charts are prepared during the design stages which describe the effect of flooding on various single compartments or combinations thereof. The safe limiting extent of such flooding is also defined.

In the preliminary design stage, the load water lines based on displacement are computed from the design gross weight and range of expected static trim angles. The hull or flotation spaces must be designed so that for any given load on the water an acceptable static flotation trim angle will result. The static trim will depend on the number and distribution of watertight compartments and the resulting center of buoyancy. Since the response of the seaplane to hydrostatic forces in the displacement range is similar to that of ship hulls, the design of seaplane hulls follows closely the procedures used in Naval Architecture. These procedures are normally based on the classical approach and involve long and tedious calculations using Bonjean curves of hull volume summed by the use of Simpson's Rule, in order to provide trim and displacement information. A standard text such as reference (1) may be consulted for a clear detailed discussion of hull design practice.

A test procedure which involves the use of models has been used in which the gross weight and center-of-gravity position are varied on the model by means of weights placed on the model. Flooding of compartments can be simulated by additional weights equal to the loss of buoyancy due to flooding. These weights may be placed directly above the center of buoyancy of the flooded compartment. Rolling moments may also be simulated in this fashion.

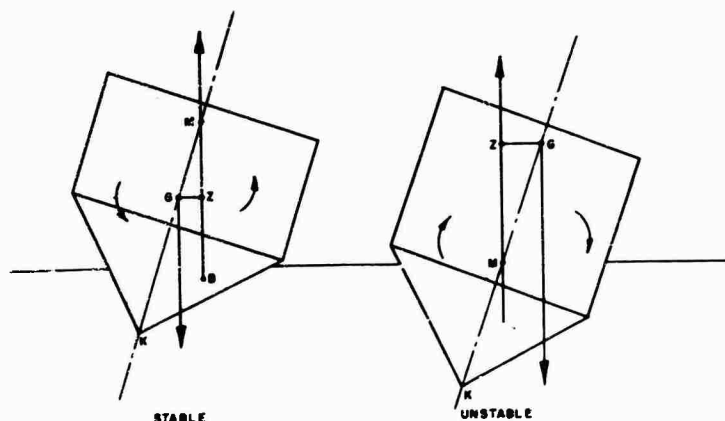
With the development of more simple charts, however, it has been possible to design hulls with less time-consuming calculations and without resorting to the use of expensive models. One such chart is a modification of the use of Bonjean curves and the procedure for their use is described fully in reference (2). In another method, a waterline is assumed for a specific trim and the sectional area is plotted as a function of the distance from the bow. The volume and the displacement are obtained by integrating this curve.

The position of the center of buoyancy from the step may be computed from the difference of the curves of forebody moment minus afterbody moment divided by the curve of normal flotation. Changes of trim will affect the buoyancy and changes of draft to correct buoyancy will affect trim. Therefore, the two computations must be conducted simultaneously.

The development of high-length beam ratio hulls in recent seaplanes has reduced the problem of providing adequate longitudinal stability to one of academic interest only. Metacentric height for longitudinal stability is computed but satisfactory results are generally obtained without major adjustments. However, at the same time, the use of a very narrow beam increases the problem of transverse static stability.

In recent years, almost all seaplanes have used the wing tip float as the primary means of providing the necessary transverse stability. The wing floats must be designed so as not to hamper the seaplane in the planing range. In addition, they must withstand any lateral upsetting moment brought about by the action of wind and wave either while the seaplane is moving or moored.

The measure of initial transverse stability is the metacentric height. This is the distance GM shown in figure 2:2.



The point M is the one about which the hull rotates when inclined. The hull is stable when M is above G. When G is above M a heeling moment exists which tends to incline the seaplane away from the upright position and an unstable condition exists. The point M can be considered fixed for angles as high as 15° but is more generally limited to 7°. In design practice, the distance BM (the metacentric radius) is mathematically expressed as:

$$BM = I/V \quad (2-1)$$

where I is the moment of inertia of the waterplane area and V is the submerged volume.

From this expression, it can be deduced that both the beam and the form of the waterplane influence the metacentric height. In a complete analysis of the metacentric height, the free surface effect of fuel tanks must be accounted for. Free surface effect amounts to raising a weight equal to that of the liquid in the tank through a vertical

Figure 2:2



distance GM. The reduction in GM for the seaplane is equal to the moment of inertia of the liquid in the tank divided by the aircraft displacement. For several tanks, the individual moments of inertia are added, then divided by the aircraft displacement. Corrections are made for the difference in specific gravity of the liquid in the tank and the liquid outside the tank, and for the surface permeability of tanks or flooded compartments.

Since the transverse stability is usually accomplished by the use of wing tip floats, the righting moment due to the wing floats is computed in addition to the righting moment of the hull. Curves of total righting moment can then be constructed for various normal, flood or wind conditions. Trim and draft changes for listing are considered negligible although theoretically, wing displacement does change the hull trim and draft.

It is possible to eliminate the use of wing tip floats by building sufficient buoyancy into the wings. The necessary buoyancy for a wing can be determined by the use of Bonjean curves superimposed with various list angles in the same fashion as trim angles are used for hull design.

## 2.3 DYNAMIC FORCES AND THE PLANING RANGE

The planing region is best understood by beginning with the flat plate which usually forms the basis of hydrodynamic investigations. Figure 2:3 shows the general type of flow that exists on a flat plate traveling at a given speed coefficient and trim angle. The flow has already reached equilibrium. The wake trails from the aft end of the plate and the water breaks away cleanly on two sides leaving the upper portion of the plate dry. In front of the planing surface the water surface rises first gently, then quickly turns upward and forward, forming a thin sheet. The streamline which separates the forward flow from the aft flow at the leading edge meets the surface at a point called the stagnation point. At this point the maximum water pressure on the surface is developed. The resulting pressure pattern is also shown on figure 2.3. The forward region of rapidly curving water under the planing plate has been given the name "spray root" by H. Wagner who formulated the theory of its formation in reference (3).

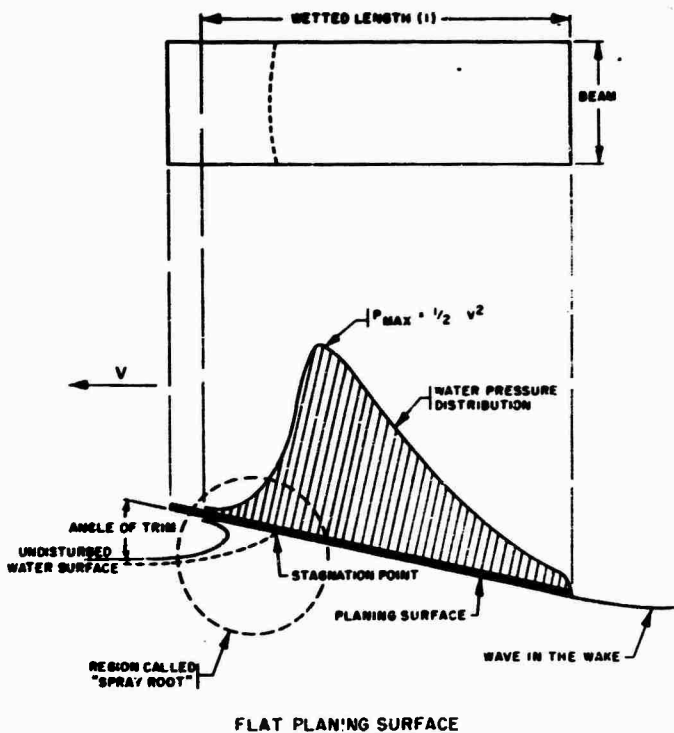


Figure 2:3

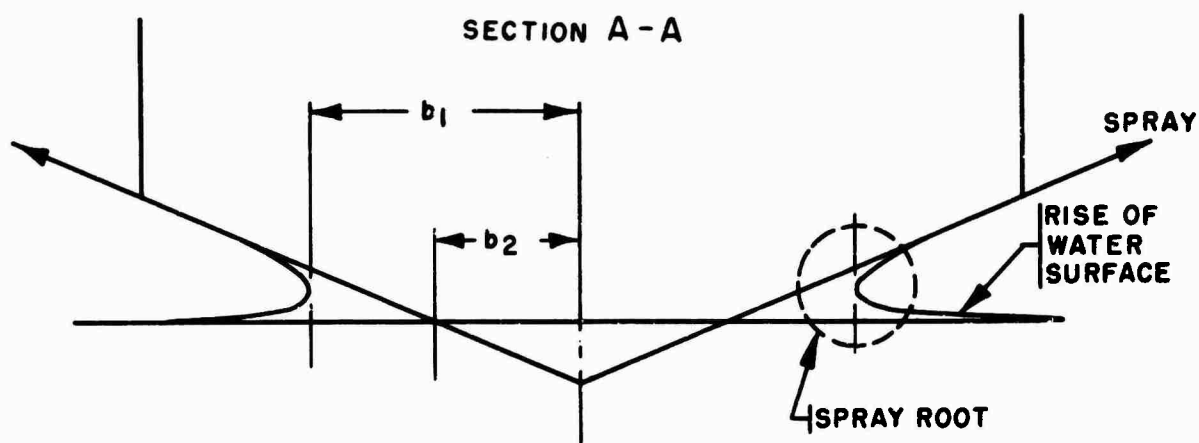
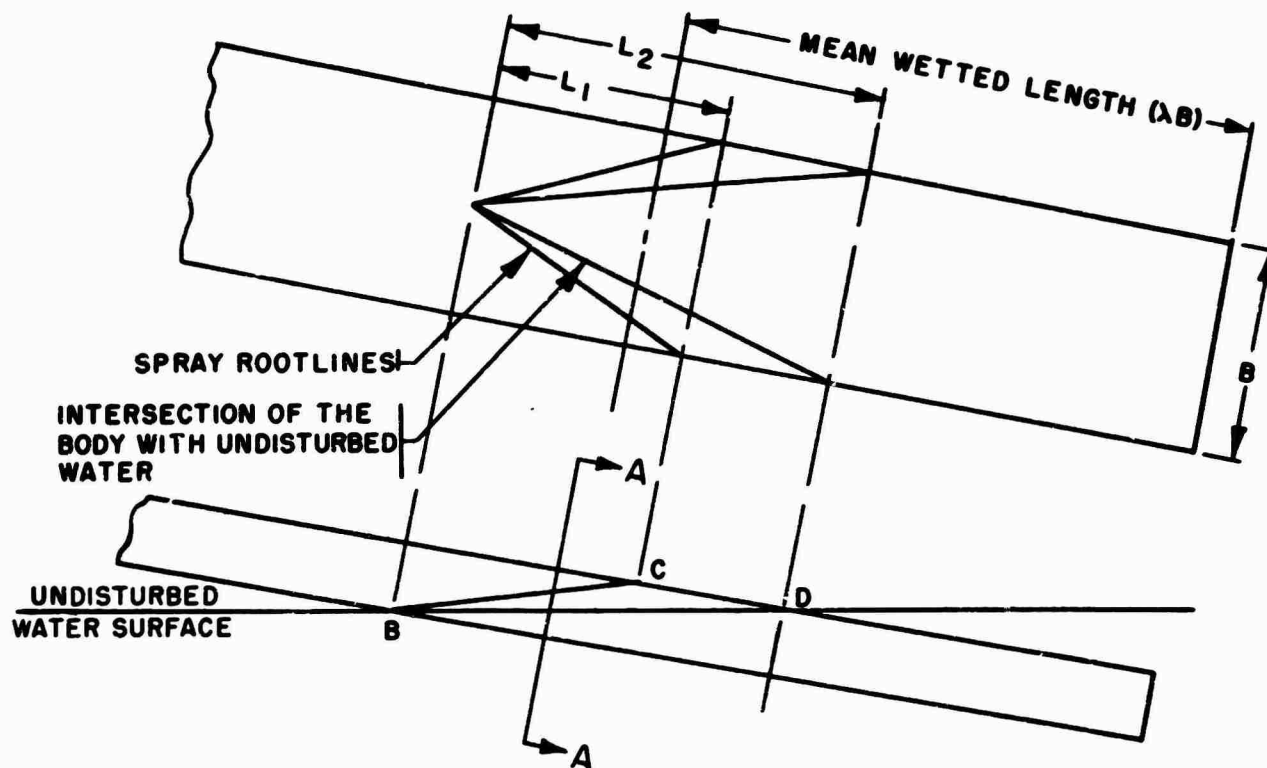
Although most theoretical work has its origin in the investigation of flat plates, the prismatic Vee section is much closer to reality. Figure 2:4 illustrates the action of the "spray root" on a prismatic Vee section. At the point B there is no discernible rise and can be assumed to lie on the undisturbed water surface. As the flow progresses in an aft direction, the water rises to the point C rather than continuing to the point D on the chine. Wagner established the relation  $b_1/b_2 = \pi/2$  from which it can be shown that  $L_1/L_2 = 2/\pi$ . Using the symbol  $\lambda = L/B$ , the following expressions are obtained:

$$\text{wetted length of keel} = B (\lambda + \tan \beta / 2 \pi \tan \gamma) \quad (2-2)$$

$$\text{wetted length of chine} = B (\lambda - \tan \beta / 2 \pi \tan \gamma) \quad (2-3)$$

Since the planing section in this latter case is prismatic, the wetted length of the chine and the keel differ. Therefore, in

practical hydrodynamics the wetted length always refers to a mean wetted length. More important than the wetted length, is the wetted area which for the case of a prismatic bottom appears in figure 2:4 as a rectangle with a triangle added to the forward



VEE PLANING SURFACE

Figure 2:4

end. This is an idealistic shape and how closely it is approximated in full scale depends on the construction of the hull bottom.

## 2.4 THE HYDRODYNAMIC FORCE

It can be shown by dimensional analysis that the hydrodynamic force acting on a submerged body, located far from any boundaries, can be expressed as follows:

$$\text{Force} = k \times \frac{1}{2} \rho V^2 L^2 f\left(\frac{VL}{\nu}\right) \quad (2-4)$$

Equation (2-4) illustrates the fact that the force is dependent on some function of the Reynolds Number. However, the seaplane does not operate at some infinite depth but rather at or near the surface of the water. When operating at or near the surface, the force is affected by gravity acting on waves and by surface tension which resists the distortion of the initially flat surface. Using dimensionless analysis the force for such a body takes the following form:

$$F = k \frac{1}{2} \rho V^2 L^2 f\left(\frac{VL}{\nu}\right) F\left(\frac{V}{\sqrt{gL}}\right) Q\left(\frac{V^2 L}{\sigma/\rho}\right) \quad (2-5)$$

The force then, is dependent on some function of three characteristic dimensionless ratios, the Reynolds number, the Froude number and the Weber number in that order. The Froude number indicates the ratio of dynamic forces to gravity forces. The Weber number indicates the ratio of dynamic forces to surface tension forces while the Reynolds number is the ratio of dynamic forces to viscous forces.

In model seaplane work, the effects of Weber number are confined to low speeds and when using very small models. In most model seaplane work, the Weber number is considered constant and equal to unity.

### 2.4.1 THE LIFT FORCE

The hydrodynamic force developed in the previous section has significance only when separated into lift and drag components. Since the Reynolds number has little influence on lift, only the Froude number is considered in the evaluation of the lift force, and is designated:

$$L = C_L \frac{1}{2} \rho V^2 B^2 \quad (2-6)$$

where the beam is used as the characteristic length and the lift coefficient is a function of the following variables:

$$C_L = f(\gamma, \lambda, C_V, \beta) \quad (2-7)$$

Mathematically, it is possible to compute the slope of the lift curve on a flat plate in terms of trim angle by the use of the complex variable in a manner similar to airfoil theory. Transformations of several planes are used so that the lift of a flat plate with an infinite trailing edge becomes in a weightless fluid:

$$C_L = f(\gamma) = \frac{2\pi \sin \gamma}{2 + \pi \sin \gamma} \quad (2-8)$$

from which the slope of the lift curve becomes:

$$dC_L/d\gamma = \pi \quad (2-9)$$

The lift is restricted to only one-half the value obtained in the case of airfoil theory since the lift acts on only one-half the plate without circulation.

Despite the apparent ease of computing the lift force even by the momentum theory, it has not been possible to analytically evaluate the lift coefficient. The value of lift is usually established by empirical analysis from planing data. Reference (4) traces many of the expressions that have been developed for analytically determining the lift coefficient both on flat plates and on prismatic Vee sections. The basic assumptions for each method are discussed as well as the factors taken into consideration. Curves are presented which show both the range of applicability and the degree of agreement for each expression. As an example, the lift of a finite flat plate has been empirically determined by the Stevens Experimental Towing Tank in terms of wetted length, trim angle and speed coefficient as follows:

$$C_L = 1.1 \left[ 0.0120 \lambda^{\frac{1}{2}} + 0.0095 (\lambda / C_V^2) \right] \quad (2-10)$$

The above equation is further modified in order to compute the lift of the prismatic Vee section.

## 2.4.2 RESISTANCE AND THE DRAG FORCE

The drag portion of the hydrodynamic force has been determined to depend on both the Froude number and the Reynolds number. In this case, the expression for the resistance can be written as follows:

$$R = k \times \rho V^2 B^2 F \left( \frac{V}{\sqrt{gB}} \right) F \left( \frac{VL}{B} \right) \quad (2-11)$$

The total resistance of a seaplane can be considered to consist of the following:

- a. Hull form drag which includes wave and eddy drag.
- b. Skin friction drag.
- c. Induced drag.

It has been experimentally determined that these three forms of drag can be accounted for by separating equation (2-11) into the following form:

$$C_D = \frac{R}{\rho V^2 B^2} = k_1 \left[ f(C_V) \right] = k_2 \left[ F(Re) \right] \quad (2-12)$$

The above relation represents the total resistance as composed of the drag due to normal pressures and that due to tangential or frictional forces. The dynamic drag due to normal pressures is related to the lift force in the following manner:

$$C_{Dd} = C_L \tan \delta \quad (2-13)$$

where the effect of wave drag, being a function of  $C_V$  is included in  $C_L$  when measured in the towing tank.

The friction drag coefficient of a seaplane is based on the concept that it is equal to the skin-friction drag of a flat plate having the same length, wetted surface area and Reynolds number as the model. The coefficient can be computed from several mathematical relationships, the selection of which depends on the range of  $Re$  and the type of flow. Reference (5) contains a complete discussion of turbulent and laminar boundary layers. For convenience, figure 2:5 has been reproduced from reference (5) in order to illustrate some of these relationships.

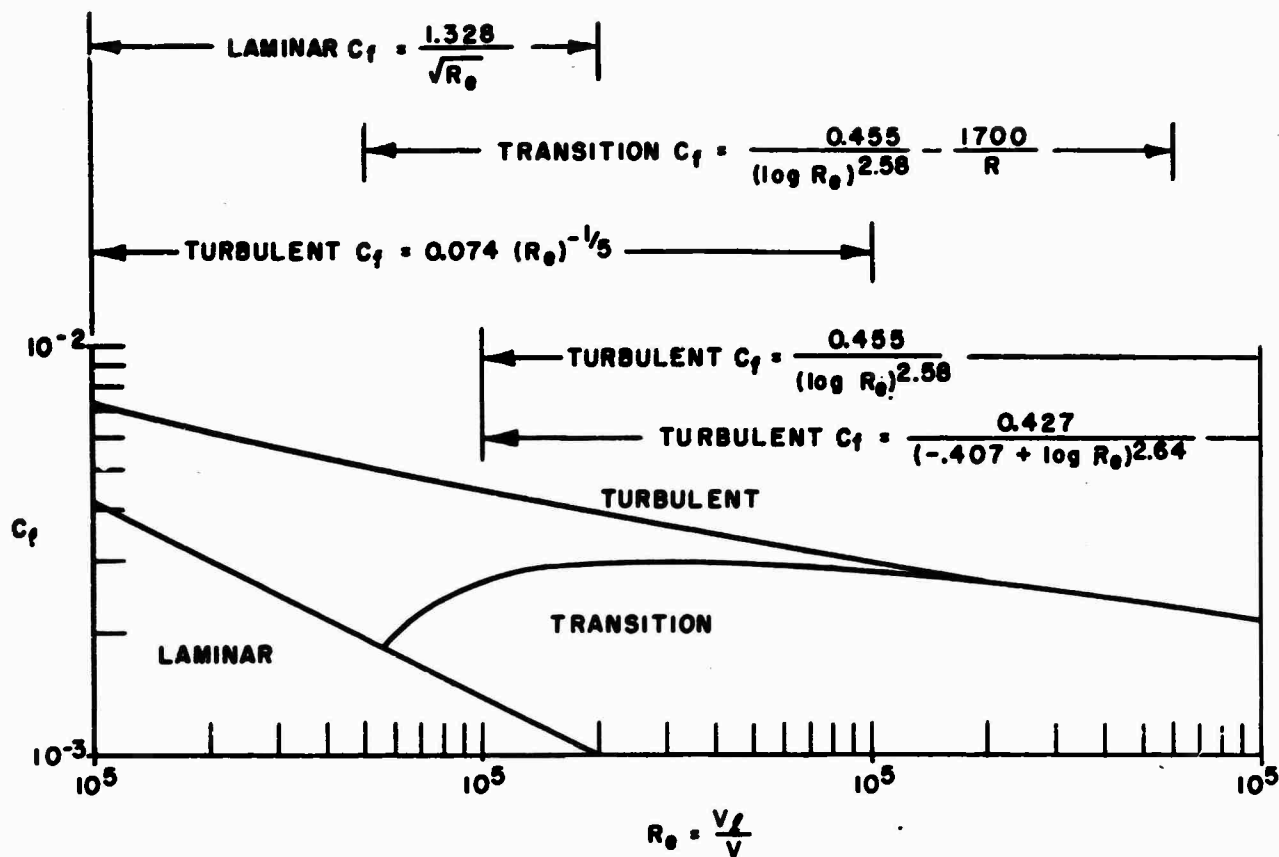


Figure 2:5

The friction coefficients read from figure 2:5 are based on wetted area and must be converted to a beam square in order to be added to equation (2-13). The change is accomplished by multiplying the friction coefficient by  $\sec$ . The final equation for total resistance then becomes:

$$C_D = C_L \tan + C_F \sec B \quad (2-14)$$

where  $\tan$  is as usual the wetted length  $L/B$ . The geometrical representation of this relation is illustrated in figure 2:6.

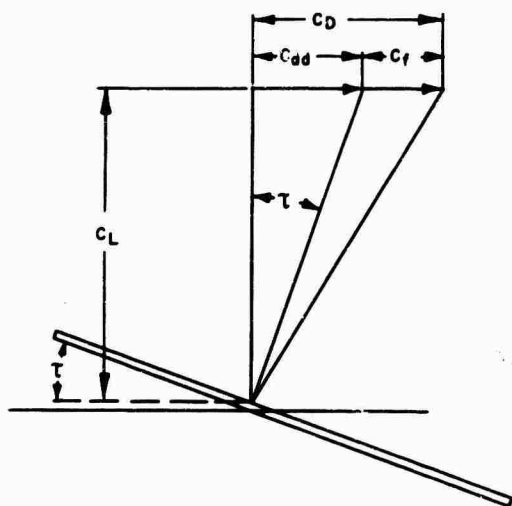


Figure 2:6



CHAPTER 3  
MODEL TESTING

- 3.1 General
- 3.2 Testing Facilities
- 3.3 Test Schedules
- 3.4 Correlation to Full Scale

### 3.1 GENERAL

In the science of Marine Engineering, successful testing of models to predict or evaluate full-scale operation was the basis for seaplane model testing almost before wind tunnel testing became the criterion for predicting full scale aerodynamic characteristics. Agencies such as the NACA and Stevens Experimental Towing Tank (ETT) operate various water tunnels and tanks and conduct tests on proposed seaplane designs. Although much of the work is devoted to testing current designs a large amount of research is carried on in basic hydrodynamics. The following sections indicate the facilities that are used in conducting hydrodynamic research and the manner in which the information so obtained is tabulated.

### 3.2 TESTING FACILITIES

The testing of model seaplanes is usually accomplished in a towing tank. The typical towing tank consists of an oblong tank of water, the exact dimensions of which depend on the testing requirements. Along the length of the tunnel a carriage is suspended on which the model being tested is carried. In smaller tanks such as those at the ETT, data can be automatically recorded or observed from the side of the tank as the carriage and model go by. In larger tanks, such as the NACA maintains at Langley, Va., several observers can ride on the carriage during the course of the test. Such an arrangement permits excellent opportunities to observe closely such phenomena as spray and longitudinal stability while moving with the model. The latter arrangement is ideally suited to the use of larger models which many authorities feel will yield better test results than those of smaller models.

Testing is not confined to towing tanks since much useful information has been gleaned from operating model seaplanes in any nearby bay or pond.

No matter what the size of the tank or carriage, arrangements are made such that the same type of information is recorded in each case. This information includes hull trim angle, resistance and heave. The carriage is such that the model can be adjusted for speed control, load on the water and center-of-gravity position. Tests for stability derivatives in rectilinear motion may be run as well as those tests for the collection of general planing data. Tests for yawing stability are conducted by setting the model at a known yaw angle and then noting the equilibrium yaw angle at

various constant speeds. A calibrated spring is used from which a yawing moment may be computed based on the difference in static and running yaw angles. The yawing moment is plotted against the running yaw angle.

Other types of towing tanks are used for various purposes. The ETT, for instance has a large square tank wherein the carriage is located on a rotating arm. This type of equipment is used to determine the maneuverability of a seaplane and the stability derivatives in curvilinear motion.

Almost all tanks have the necessary equipment with which to simulate waves of varying period and amplitude. The equipment consists of a triangular plunger linked to a motor and timer. Wave amplitude is governed by the depth of submergence of the plunger while wave period is controlled by the rapidity of application of the plunger. Recent development in towing tank technique have resulted in a wave making machine which more truly represents the wave patterns encountered in full scale conditions. The amplitude is not constant but varies so that a wave train of any desired average height can be produced. The chief drawback of any wave making machine is that the model direction of motion is always directly into the wave pattern. Testing a seaplane traveling directly into head seas, gives an evaluation of the seaplanes capabilities under the most severe conditions. In full scale operations, seaplanes would rarely travel directly into head seas or large swells.

At the University of Colorado, a circular tank has been constructed which contains a wave-making machine. The outstanding feature of this tank is that the overhead track which supports the carriage can be rotated. In this manner the model seaplane can be made to cross the waves at any desired angle.

Equally as important as the towing tanks, are the water tunnels wherein the model is stationary and the water flows past the model. Some water tunnels have a free surface while others have no surface, being completely enclosed like a wind tunnel. In both types, observers windows are available sometimes from below but more often from the side. A complete closed-flow tunnel may be used to determine the cavitation characteristics of submerged hydro-foils and hydro-skis.

In addition to the equipment used in both tanks and tunnels to collect quantitative data such as lift, drag and

pitching moments, there are usually facilities for obtaining photographs of spray, wetted area or other phenomena occurring either above or under water.

A good deal of excellent data has been obtained by the use of free-flight and radio-control models. The radio controlled model, although not as well suited to the gathering of quantitative data as the more captive towing tank model, approaches the ideal pilot-induced response technique that characterizes full-scale testing. There are many limitations to the free-flight or radio-control testing technique but several contractors have felt that the results more than justified the time and money spent.

### 3.3 TEST SCHEDULES

In testing model seaplanes, a large overall program may be required in order to determine the hydrodynamic characteristics of the model. Perhaps only a single characteristic may be required, or else the effect on performance of some change to the hull is required. The present section will describe those tests which deal with the overall hydrodynamic characteristics of a seaplane model. Tests for a single characteristic or for the effect on a single characteristic of some change to the model are relatively simple and will depend on the characteristic being tested.

There are in general three systems of obtaining and presenting the overall basic hydrodynamic characteristics of seaplane models. The term basic characteristics refers to the lift, resistance, heave, trim, and pitching moment.

a. Specific Tests. Specific tests are made to verify and present in graphic form the characteristics of a specific design, at a specific load and at a specific take-off speed. It is the simplest test and it presents the most usable data with a minimum of calculations. The test speed is related to full scale operation by the Froude law of similarity:

$$V_m/V_{FS} = \sqrt{L_m/L_{FS}} = \lambda^{-1/2} \quad (3-1)$$

where m denotes model, FS denotes full scale and  $\lambda$  is the scale factor. The CG location and model weight are adjusted from the following relation:

$$W_S = \Delta_S = \lambda^3 W_m \quad (3-2)$$

Wing lift corrections are based on a "parabolic unloading curve" which is expressed in the following relation:

$$\Delta = \Delta_0(1 - v^2/V_G^2) \quad (3-3)$$

at  $V_G$  (getaway speed) the load on the water is:

$$\Delta = 0$$

and  $\Delta_0$  is the static load on the water. This relationship simulates the lift of the wings during the take-off run and can be induced on the model by the use of a hydro-foil which will completely balance the weight of the model at getaway speed.

With the model "free-to-trim" (i.e. free to seek its own equilibrium trim angle), measurements are made of its change in draft (or heave) from static draft, the trim angle and the resistance. The quantities are then plotted as shown in figure 3:1. To check those angles that the hull assumes when free to trim, runs are made at fixed trim and measurements are made of the change in draft, pitching moment and resistance.

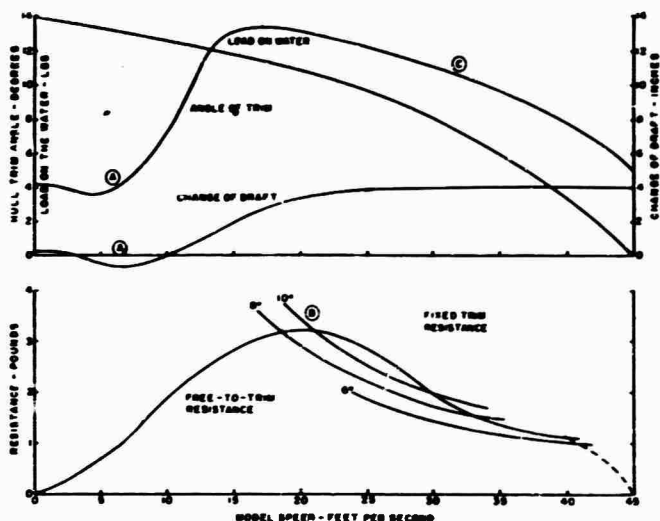


Figure 3:1

On figure 3:1 it will be noted that at point A, at low speeds, the curves of both the angle of trim and change of draft dip. This is due primarily to suction generated by water flow around the curved bow sections of the hull. In certain hulls a combination of such dips might indicate an adverse diving tendency. Point B is the "hump" and can be seen to be very nearly coincident with maximum trim. The angle of trim between hump speed and the point C is determined by the stern post angle and the wake configuration which normally gives a broad low peak to the resistance curve. It is generally concluded that the broad peak resistance curve is most suitable. Conditions which produce excessive high trim angles at hump speeds tend to produce excessive low trim angles at high speed. This produces a sharp peak in the resistance curve at hump speed with a tendency towards a second sharp rise at high speed.

b. General Tank Test. General Tank Test was devised by NACA to give data which could be used for a wide range of loads, speeds and hull sizes. The lack of applicability is the chief drawback of the specific tests in that the data could not be used for loads and speeds other than those used in the tests. In the General Tank Test all data are put in the form of non-dimensional coefficients as defined in section 1.3. Therefore, the data has more range of applicability than the data of the Specific Test.

The coefficients  $C_R$  and  $C_M$  are determined by tests and plotted against  $C_V$  with  $C_\Delta$  as a parameter. A sample of this plot is shown in figure 3:2. A similar plot must be made for each trim angle tested. From figure 3:2, it is not readily apparent where the best value of  $R/\Delta$  lies, which is a measure of

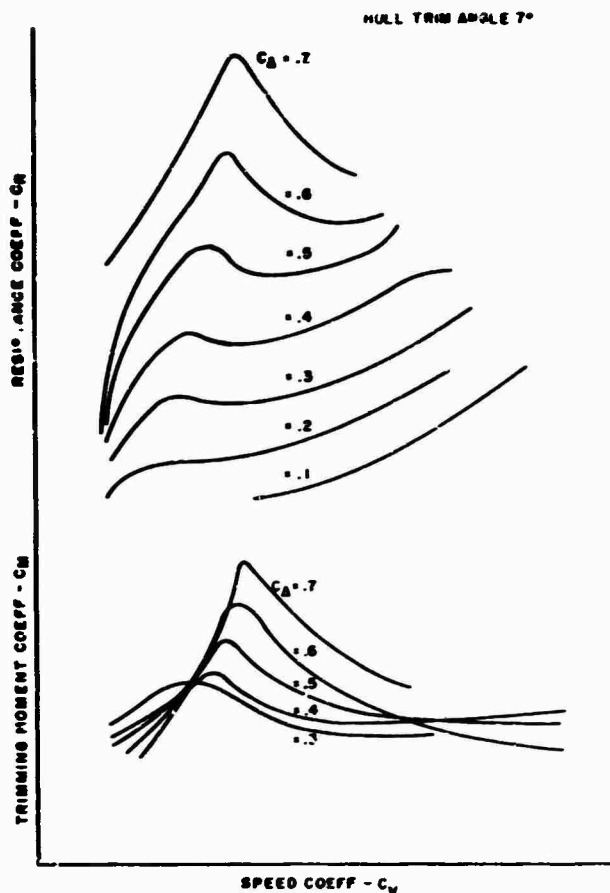


Figure 3:2

c. Stevens Collapsed Data Test. The Stevens Collapsed Data Test originated at Stevens Institute of Technology and was developed to give the data of the General Test type with a lesser number of test points in a more compact form. Collapsed data was the outcome of trying to get more useful data from smaller tanks. Figure 3:4

the planing efficiency. Therefore, in order to indicate the best planing efficiency or value of  $R/\Delta$  figure 3:3 is an alternate method of plotting the data contained in figure 3:2. The data of figure 3:3 are for a speed coefficient of 3.5 and a separate chart is prepared for each speed coefficient used during the tests. A large and extensive testing schedule is required in order to cover the broad field for which the data are intended. The data must be corrected from general test charts into the form of specific test charts for proper analysis, while the number of points which can be obtained for a specific problem are rather small.

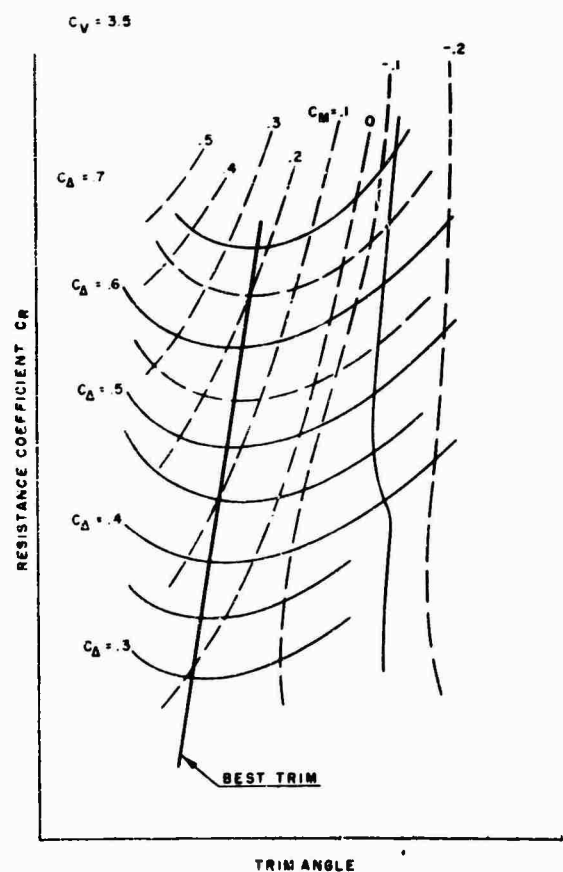


Figure 3:3

MODEL NO \_\_\_\_\_ CG LOCATION  $C_{A0}$  \_\_\_\_\_  
 MODEL BEAM \_\_\_\_\_ K/L \_\_\_\_\_ DATE \_\_\_\_\_

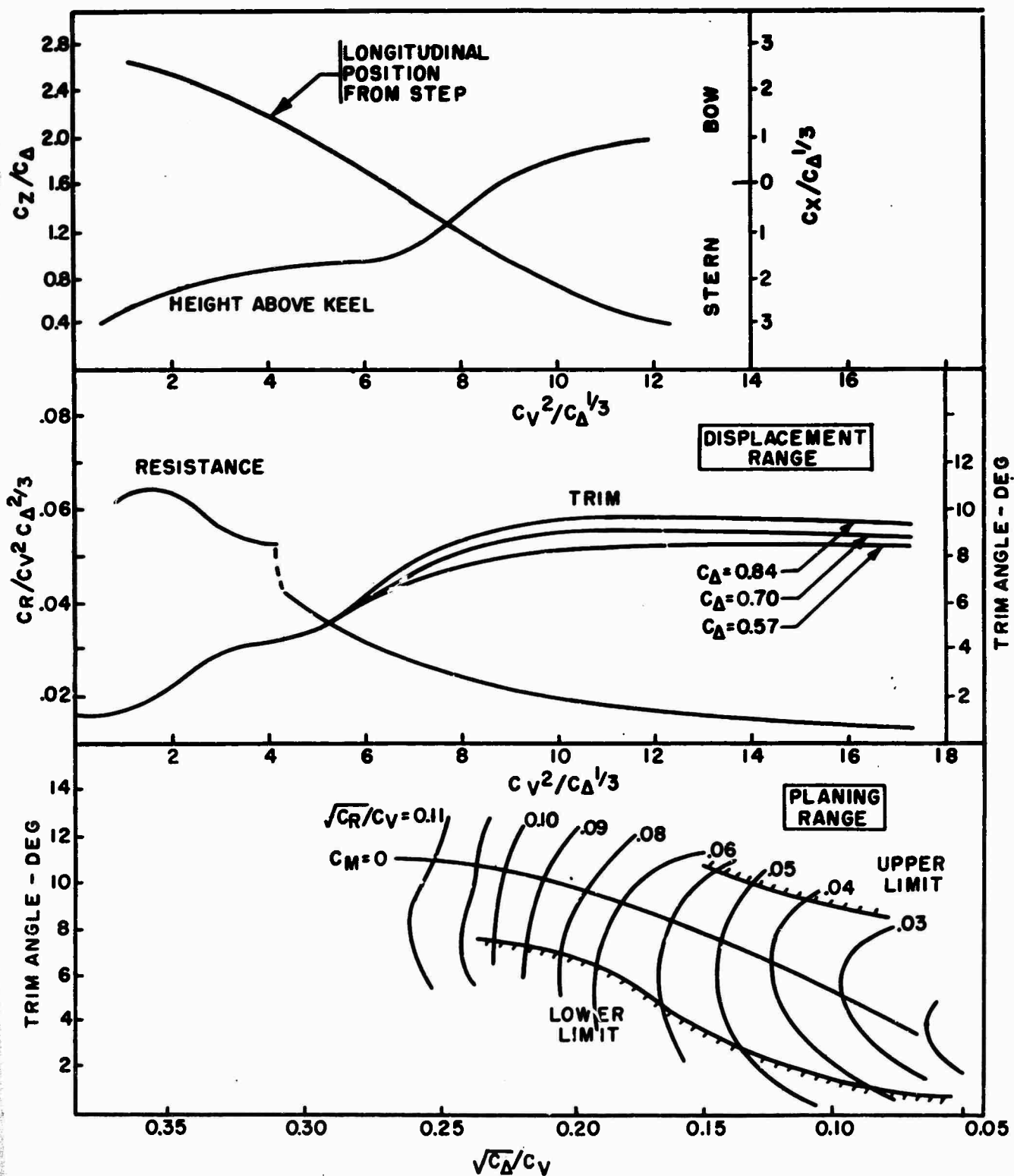


Figure 3:4



illustrates the manner in which the data is presented. One of the distinguishing features of figure 3:4 is that hull performance is considered in two ranges, above and below hump speed. The middle diagram of figure 3:4 represents the trim and resistance below hump speed (i.e. the displacement range). In this range the attitude of the hull is determined by the hull interaction with the wave pattern it creates. Since large moments would be required to modify the naturally high trim angle encountered in the displacement range, and since aerodynamic controls are weak in this range and cannot supply the required moments, the hull is tested free-to-trim. In the displacement range the resistance coefficient is mainly a function of the Froude number:

$$R / \frac{1}{2} \rho V^2 L^2 = f(V^2/gL) \quad (3-4)$$

where  $L$  is any characteristic length. If  $L$  is defined as  $(\Delta/w)^{1/3}$ , substitution in the above expression with the use of NACA coefficients yields the following expression:

$$\frac{C_R}{C_{\Delta}^{2/3} C_V^2} = f\left(\frac{C_V^2}{C_{\Delta}^{1/3}}\right) \quad (3-5)$$

The center plot of figure 3:4 illustrates that one resistance curve can represent a considerable range of loadings. Excessive loading may give a higher resistance and higher trim but once the curve has been established, relatively few check points will be required to indicate any deviations.

At speeds past the hump, particularly at getaway, aerodynamic controls are effective and selection trim angles are possible. For this reason, tests in the planing region are conducted at a series of fixed trims. Also, in this range, the resistance may be considered to be essentially independent of the Froude number and dependent on induced drag which is a function of the loading. Such a simplification yields the following expression:

$$\frac{R}{\frac{1}{2} \rho V^2 L^2} = f\left(\frac{\Delta}{\frac{1}{2} V^2 L^2}\right) \quad (3-6)$$

Substituting NACA coefficients, the following results are obtained:

$$\sqrt{C_R} / C_V = f(\sqrt{C_{\Delta}} / C_V) \quad (3-7)$$

Test results are computed and the above relation is plotted as a curve for several trim angles. The results are then cross plotted as shown on the bottom diagram in figure 3:4.

### 3.4 CORRELATION TO FULL SCALE

Section 2.4 briefly discussed the determination of the hydrodynamic force and its separation into lift and drag forces. The separation of the Froude and Reynolds numbers effects makes it possible to run model tests based on the similarity of the Froude number, since it is mathematically impossible to equate model and full scale to both the Froude and Reynolds number. After the equality of the Froude number has been established, corrections can be made for Reynolds number variation between model and full scale.

In full scale testing turbulent flow is almost always present but in certain phases of model testing the flow can be at least partly laminar. In order to keep all resistance computations on the same curve for friction corrections from model to full scale (see figure 2:5), turbulent flow is induced in the model by towing a wire in front of the model. This practice eliminates any uncertainty in computing full scale resistance values.

In spite of elaborate towing tank procedure used to ensure turbulent flow, the problem of equating model and full scale has been complicated by a lack of knowledge of full-scale roughness resistance. This has been the principle reason for testing models as large as possible. Unfortunately it has not always been possible to use large models. As yet no standard procedure has achieved any degree of wide-spread acceptance, concerning full scale roughness resistance. In preliminary design practice the frictional resistance has been increased by as much as 25% to account for full scale surface roughness.

When the range of test Reynolds number has been determined, a suitable exponential relationship for the friction coefficient within that range might take the following form:

$$C_f = 0.074(R_e)^{-2}$$

This is the Prandtl-Von Karman experimental formula. This type formula is easier to use than the Schoenherr friction formula which requires a knowledge of wetted area.

By making notations for model and full scale as in section 3.3 the friction coefficients of the model and full scale can be equated in turbulent flow as follows:

$$\frac{(C_f)_{FS}}{(C_f)_M} \left( \frac{Re_m}{Re_{FS}} \right)^{-2} \left( \frac{\dot{V}_m L_m}{V_{FS} L_{FS}} \right)^{-2} = (\lambda^{-2} \cdot \lambda^{-1})^{-2} = \lambda^{-3}$$

For a different range of Reynolds number, the above formula can be approximated more closely by changing the exponential to another suitable value. The following series of steps may then be used to correct to full scale resistance:

- a. Total measured resistance at trim angle = A
- b. Resistance due to load  $\Delta = \Delta \tan \gamma$  = B
- c. Frictional resistance = A-B
- d. Corrected frictional resistance  $(A-B)\lambda^{-3}$  = C
- e. Total corrected resistance = B+C

The total resistance is then converted to coefficient form using model speed and dimensions and plotted as discussed in section 3.3. The data can be converted from the coefficient form to full scale when desired by multiplying by the full scale speed and dimensions. Full scale resistance can also be obtained by multiplying the corrected total model resistance by the scale ratio cubed ( $\lambda^3$ ).

The above procedure is the one recommended in reference (6) for correcting to full scale the planing range past hump to getaway. Since Froude number agreement is much more critical in the displacement range, and since in this range the friction drag is small, model resistance data in this range can be corrected by the factor  $\lambda^3$  without reference to the friction coefficient.

Full scale resistance is frequently ascertained only deductively. Model performance such as take-off time based on model resistance is computed. In full scale tests, if the take-off time is in fair agreement with model data, then the resistance of the full scale article must be in at least fair agreement with model resistance. The basic quantity of resistance has never been tested full scale. Only performance is tested which is then indirectly a measure of resistance depending on the degree of correlation between model and full scale.

Much has been said about "scale effect" which has been defined as the detectable difference between full scale performance and model performance. Reference (7) takes the position that there may be such a thing as "scale effect" but if so, it must be rigorously defined. As a general rule, if the model accurately duplicates the full scale article then results will be directly comparable with no discernible difference. This view has been predicted on a comparison of many model and full scale tests which indicated that the only detectable difference was one that was within the limits of the experimental accuracy.

There are many complications in the determination of full scale drag. In fact, the problem of drag and resistance, like the lift problem is better handled empirically.

## CHAPTER 4

### FULL SCALE TESTING

- 4.1 Programming
- 4.2 Water Maneuvering
  - 4.2.1 Discussion
  - 4.2.2 Test Procedure
    - 4.2.2.1 Instrumentation
    - 4.2.2.2 Coordination
  - 4.2.3 Presentation of Results
  - 4.2.4 Analysis
- 4.3 Spray Characteristics
  - 4.3.1 Discussion
  - 4.3.2 Test Procedure
    - 4.3.2.1 Instrumentation
    - 4.3.2.2 Coordination
  - 4.3.3 Presentation of Results
  - 4.3.4 Analysis
- 4.4 Longitudinal Stability During Take-Off
  - 4.4.1 Discussion
  - 4.4.2 Test Procedure
    - 4.4.2.1 Instrumentation
  - 4.4.3 Presentation of Results
  - 4.4.4 Analysis
- 4.5 Longitudinal Stability During Landing
  - 4.5.1 Discussion
  - 4.5.2 Test Procedure

- 4.5.3 Presentation of Results
- 4.5.4 Analysis
- 4.6 Longitudinal Control
- 4.7 Directional Stability and Control
  - 4.7.1 Discussion
  - 4.7.2 Test Procedure
  - 4.7.3 Presentation of Results
  - 4.7.4 Control
- 4.8 Lateral Stability and Control
- 4.9 Take-off Performance
  - 4.9.1 Discussion
  - 4.9.2 Test Procedure
    - 4.9.2.1 Instrumentation
  - 4.9.3 Presentation of Results
  - 4.9.4 Analysis
- 4.10 Hydro-skis and Hydro-foils
  - 4.10.1 General
  - 4.10.2 Testing and Applications
- 4.11 Rough Water and Sea Worthiness
  - 4.11.1 General
  - 4.11.2 Theory of Impact
  - 4.11.3 Pressure Distribution
  - 4.11.4 Full Scale Testing
  - 4.11.5 Elastic Response
  - 4.11.6 Waves
  - 4.11.7 Seaworthiness

## INTRODUCTION

The sub sections which follow are devoted to those full scale tests which are either normally conducted on current seaplanes at the Naval Air Test Center or considered feasible for future seaplanes. For each hydrodynamic characteristic a general discussion serving as background, a test procedure, a method of presenting results and an analysis of recorded data have been included.

### 4.1 PROGRAMMING

The program which is prepared as a guide for the conduct of a test or series of tests, must interpret the requirements of a test directive into such action that will provide the desired information. The test program, therefore, becomes the principle organ of successful programming and is locally prepared on the basis of the project directive.

A project directive establishes the requirement for both PTR and BIS projects. When hydrodynamic tests are to be conducted under a BIS project, test directive 5-5 of reference (8) specifies in general terms which tests shall be conducted. Projects established under a PTR are usually of a wide variety. A PTR project might for instance request a rough water evaluation, a full hydrodynamic investigation of an experimental seaplane or an evaluation of a modification installed to improve certain hydrodynamic characteristics. Reference (9) contains no hydrodynamic test directives and therefore PTR project directives usually contain more detailed information.

Based on the requirements of the project directives, the test program sets forth tests that must be performed in order to comply with the project directive. The form of the test program is specified in the "Flight Test Form Book" and should be as complete as possible. The information contained in the test program must specify in sufficient detail both the tests to be conducted and the conditions under which the tests will be conducted. Details should be specific but still allow a measure of freedom in which to carry out the test program. Any major deviation from the test program requires a submission of a new or modified test program. In preparing the test program figure 4:1 is presented as a guide to determine the basic instrumentation required to collect data for the hydrodynamic tests shown. The quantity of data to be collected during the project will vary.



MEASUREMENT	TEST	TAKE-OFF AND LAND LONGITUDINAL STABILITY AND CONTROL	DIRECTIONAL STABILITY AND CONTROL	LATERAL STABILITY AND CONTROL	TAKE-OFF PERFORMANCE	SPRAY	MANEUVERABILITY	SKIS AND HYDRAFOILS	RATE-OF-SINK, IMPACT, PRESSURE
HEEL ANGLE				X		X			
TRIM ANGLE		X			X			X	X
FUEL REMAINING		X	X	X	X	X		X	X
AIRSPEED		X	X	X	X	X	X	X	X
WATERSPEED		X	X	X	X	X		X	X
ELEVATOR POSITION		X			X			X	
RUDDER POSITION			X		X			X	
AILERON POSITION				X				X	
ELEVATOR FORCE		X			X				
RUDDER FORCE			X						
FLAP POSITION		X	X	X	X	X	X	X	X
NORMAL ACCELERATION								X	X
LONGITUDINAL ACCELERATION		X			X			X	X
ANGULAR ACCELERATION		X	X	X				X	X
ENGINE RPM			X				X	X	
ENGINE MAP			X				X	X	
ENGINE BMEP OR TORQUE			X				X	X	
TIMER					X		X	X	X
HULL BOTTOM PRESSURE TAPS									X
RATE-OF-DESCENT (EXTERNAL)									X

Figure 4:1

Prior to preparing the test program, much information can be gleaned from examining the following documents as they pertain to the hydrodynamics of the seaplane undergoing tests:

- a. Contractor's flight reports.
- b. Pre-Demonstration reports.
- c. Part I and II SR-38 Demonstration reports.
- d. Contractor's report of predicted hydrodynamic characteristics.
- e. Contractor design reports.
- f. MIL Specs. for hull design (ANC-3, MIL-D-8629).

From the information provided by these reports, a test program can be prepared so that the data obtained during the tests is directly comparable with the contractor data. These reports also provide the guides required by test personnel to remain within the envelope established by contractor tests.

Once the outline of required tests has been prepared, individual tests should be arranged in a logical order since many tests can be run concurrently. For instance, the information obtained from fixed elevator take-off runs can be used for both take-off performance and for longitudinal stability. The manner of collecting data and the methods used to present the results, must also be considered.

The final report submitted must adequately supply the information requested by the project directive. The information required may be qualitative or quantitative. In either case the Flight Test Form Book should be used for preparing both the test program and the final report.

## 4.2 WATER MANEUVERING

### 4.2.1 DISCUSSION

Maneuverability is a measure of the seaplanes ability to proceed from the ramp or mooring position to the take-off area and return to its assigned position after landing. A qualitative estimation of maneuverability can be determined by actually maneuvering around some judiciously placed buoy and noting the facility with which the seaplane can be moved into a mooring position. The facility with which the seaplane is maneuvered, may be enhanced by the use of auxiliary equipment such as hydro-flaps and reversing propellers. The degree to which the use of auxiliary equipment improves maneuverability can be noted during maneuvering.

Throughout the tests, attention should be paid to the spray characteristics and any adverse effects thereof on pilot visibility, engines, propellers and on any portion of the aircraft such as hatches, wheel wells, etc. Taxiing runs should also be made at various angles to the wind in order to observe spray effects and the degree to which they effect the ease of maneuvering.

### 4.2.2 TEST PROCEDURE

Quantitative testing for low speed maneuverability is based on a method developed by the British Marine Aircraft Experimental Establishment. The method consists of turning the airplane through a  $360^{\circ}$  circle and noting the time required for the turn and the diameter of the resulting circle. The aircraft is started in a turn with specified power conditions. After the turn has been stabilized, life jacket dye marker is released and the pilot starts a stop watch as some prominent landmark passes the pilot's windshield. Timing continues through  $360^{\circ}$  until the same landmark once again appears in the pilot's windshield in the same relative position. The  $360^{\circ}$  turn can be measured from the cockpit by the use of a gyro stabilized compass or a radio compass turned to a nearby station. However satisfactory results are obtained by noting some prominent landmark through an NACA visual trim scope. The trim scope has a vertical line and is columnated which makes it easier to sight an object through  $360^{\circ}$  with little error.

The motion of the plane through the water and the dye marker flow behind, makes a distinctive pattern which can be photographed from the air. The photography is best accomplished from a helicopter flying as nearly vertically above

the pattern as possible. The height of the helicopter should be approximately 500 ft but the exact height is governed by the requirement that all the pattern and the test aircraft be included in the photograph. The diameter of the resulting pattern may be determined by the use of scale factors from either the fuselage length or wing span. Oblique photographs should not be used since additional distortion in the diameter is introduced.

The turning circles are made both left and right with the inboard engines idling while the outboard engine(s) are gradually increased by uniform increments of RPM for each turn up to maximum RPM. During the testing, the elevator and ailerons are usually held neutral and the rudder used to assist the turn. The maneuverability evaluation should be made first without the use of auxiliary equipment such as hydro-flaps and reverse pitch. Such a procedure will indicate the minimum turning diameter that can be made in the event of equipment failure. However, the maneuverability may be determined using all or a part of the auxiliary equipment. In the case of the P5M, maneuverability was tested using hydro-flaps but not reverse pitch. In the case of the R3Y the reverse pitch capabilities were such that turning circles using reverse pitch were almost academic. In future seaplane designs, turning diameters as well as the conditions under which the diameter can be obtained will probably be specified in the contract.

It is difficult to obtain turning diameters in rough water. Therefore, turns in rough water are usually limited to a record of only the time to turn through 360°. It should be possible to use the helicopter and trailing dye technique in winds up to 10-15 kt, but any delay, by the helicopter, in photographing the resulting pattern will result in the pattern being dissipated by the action of wind and wave. It is recommended that turning diameter tests be conducted under calm conditions (wind 0-5 kt).

An additional complication is that the resulting patterns in rough water are usually not circles but ellipses. In the case of elliptical patterns the use of the minor axis for the diameter is believed to be sufficiently accurate. At higher power settings the patterns tend to become circles again.

The accuracy of diameter measurement under the conditions of the test is considered to be better than plus or

minus 0.25% and the ability to reproduce a turn under the same conditions is about the same. During the process of obtaining quantitative data, observations of water maneuverability are especially important. Items to be observed by a qualified witness include, the maximum crosswind beyond which wing tip floats will submerge; the ability to hold course at various wing angles including downwind; control deflections; and the degree of control deflections required to maneuver.

#### 4.2.2.1 INSTRUMENTATION

Figure 4:1 shows the type of data that should be recorded during water maneuvering tests. For each 360° turn the pilot records the following information:

- a. Engine RPM on each engine.
- b. Wind magnitude and direction.
- c. Sea state.
- d. Position of each surface control.
- e. Position of auxiliary control such as hydro-flaps.
- f. Time for 360° turn from stop watch and time of day for correlation with helicopter.

#### 4.2.2.2 COORDINATION

To ensure successful tests, coordination is necessary between the pilot of the test vehicle, the helicopter pilot and the photographer. This coordination can best be achieved by a conference prior to conducting the test. Radio communication between test vehicle and helicopter should be established in order that run numbers be simultaneously recorded. The run number must also be identified on the film. The photographer must be briefed on the approximate number of shots that will be taken and the type of views that are required. When using a K-20 type camera, identifying information must be written on the negative in order that later identification can be made. Coordination must also exist within the test vehicle. The station where the dye marker will be released must have adequate communications with the pilot in order that the dye marker not be released prematurely.

### 4.2.3 PRESENTATION OF RESULTS

Results may be presented in tabular form. The table will include, for each turn made, the direction of turn, the left engine RPM, the right engine RPM, the time for 360° turn, the average diameter of the turn and the dimensionless ratio  $D/L$

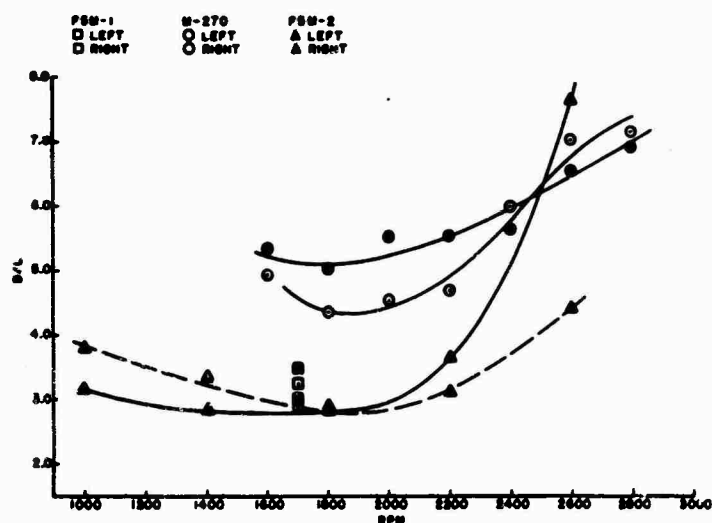


Figure 4:2

where  $D$  is the diameter and  $L$  is the length of the seaplane. The graphical method is used to show the diameter of the turn versus RPM or time to turn through 360° versus RPM. Figure 4:2 presents a plot of the ratio  $D/L$  versus RPM. An alternate method of presentation consists of plotting by the use of dimensionless coefficients. The diameter of the turn is divided by the hull length and is  $D/L$ . The quantity obtained above is plotted versus the Froude number. The Froude number is obtained by computing the circumferential speed which is the length of the circumference of the circle divided by the time obtained to travel the entire 360°. The speed is in feet per second. The Froude number is then the speed in feet per second divided by the square root of the product of the acceleration of gravity and some characteristic length which is normally the wetted length of the hull. The Froude number then is  $V/\sqrt{gL}$ . Figure 4:3 illustrates the type of curve that results from plots of  $D/L$  versus  $V/\sqrt{gL}$  for several full scale seaplanes.

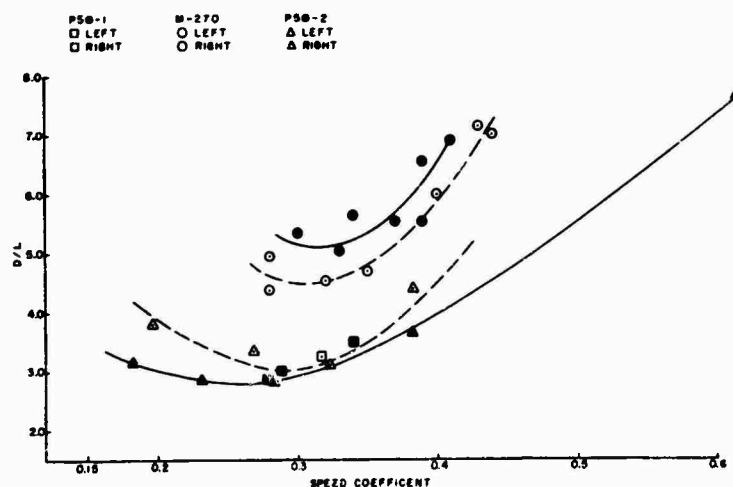


Figure 4:3

#### 4.2.4. ANALYSIS

An investigation and comparison has been made in reference (10) for various types of seaplanes. From this comparison it is concluded that below a Froude number of 0.3 the D/L is constant. Figure 4:2 does not quite bear out this conclusion. There is a tendency for the D/L ratio to increase below a Froude number of 0.3 but the minimum D/L is very close to a Froude number of 0.3.

The data for figures 4:2 and 4:3 have been obtained from turning circle tests of the P5M-1/2 and the M-270. For the data that was immediately available there is general agreement between the P5M-1 and the P5M-2. The M-270, however, shows larger turning diameters due principally to the higher  $l/b$  ratio of the M-270 and the ineffective hydro-flaps. The minimum D/L for the M-270 could possibly be improved by a larger and improved hydro-flap. In the case of the M-270, figure 4:3 shows a constant difference between right and left hand turns. Left hand turns can be made in a smaller diameter all other things being equal. This is basically due to the torque in reciprocating engines which creates a rolling moment to the left thereby placing the inboard wing tip float in the water and creating additional drag which helps to "tighten" the turn. In a right turn this same torque is causing the left wing tip float to touch the water before centrifugal force causes it to do so, thereby creating drag on the outboard side and making the diameter of the right hand circle larger than that of the left, all other things being equal. This is a generalization which should not be evident in turbo-jet seaplanes. The difference in the right and left hand turns appears to be a function of the hull length, the thrust arm and the forward speed. The case of the P5M-2 in figure 4:3 does not bear out the above analysis. In such a case, once it has been decided that the data is correct, possible sources of erratic behavior should be investigated. In the case of the P5M-2 the exhaust stack of the APU gas-turbine unit is offset to the left side of the airplane centerline. In such a position and at low forward speeds it might be possible that the thrust for the APU is such as to actually make it easier to turn to the right than to the left, all other things being equal. A slight difference in full hydro-flap deflection between the left and the right hand hydro-flap might also account for a variation in behavior. Suffice to say the water flow patterns are complex and influenced by gross weight and wind. Trends may be evident but each case must be examined on its own merit.



## 4.3 SPRAY CHARACTERISTICS

### 4.3.1 DISCUSSION

The spray thrown up by a seaplane during its take-off or landing run can do extensive damage to propellers, engines, flaps, tail and the hull itself. Not only is spray damage important, but the ability of water to cling to convex surface curvature can cause excessive resistance thereby lengthening take-off distances.

Spray on the forebody of a seaplane consists mainly of a bow spray and a main spray. As the seaplane progresses from the displacement to the planing range, the spray patterns gradually shift aft. The bow spray disappears while the mainspray becomes affected by the step area. Just prior to reaching getaway speed the main spray blends with the afterbody wake thereby forming the typical roach or "rooster tail".

As power is applied for take-off, the seaplane hull assumes increasing trim angles. The water surface strikes the bow at rather large incidence angles producing high local pressures. These pressures cause the water to flow in a thin sheet along the bottom of the hull in an outward

and aft direction. This sheet of water breaks away from the hull at the chine and forms the spray blister. Figure 4:4 illustrates the composition of the mainspray from a seaplane forebody as it exists during some portion of the planing range and after the bow spray disappeared. The composition of the mainspray as shown in figure 4:4 is of primary concern to the designer. During full scale tests, the component parts of the mainspray are rarely detectable and the main consideration is the height of the main blister at each speed.

At each speed, the seaplane produces a characteristic spray blister and a wake. Since only the blister affects the hull, these individual blisters are determined and an envelope is constructed which encompasses

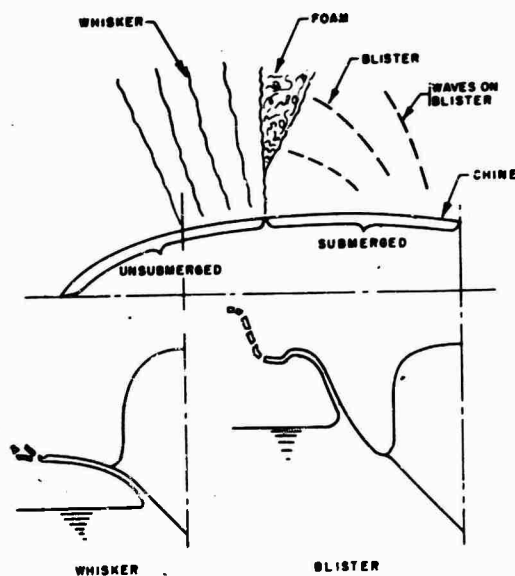


Figure 4:4

all the individual blisters. This curve is referred to as the mainspray envelope. Reference (11) contains a discussion of seaplane spray characteristics.

As the seaplane passes through the displacement range, to the planing range and finally to getaway speed, the mainspray blisters gradually increase in height then decrease and finally fall aft. Generally after planing speed is reached and hump speed is passed the mainspray is far enough aft so that no damaging spray is encountered anywhere except possibly on the tail.

At full power take-off it is quite common for the propeller slipstream to pick up water from the blister and create clouds of light spray. In interpreting spray blisters it is essential that light spray be differentiated from heavy "green water" which is the more damaging of the two.

### 4.3.2 TEST PROCEDURE

The basic technique for investigating full scale spray results is derived from towing tank procedure. This procedure consists of taxiing the seaplane at constant speeds and photographing the spray pattern from an accompanying boat. Speeds should be in roughly 10 kt increments from zero to hump speed with sufficient increments past hump speed to establish the complete envelope. In a full analysis of a large hull type seaplane, photographs from the side, the front and overhead are required. However, due to the additional work required in obtaining data for a full analysis, photography is normally limited to hull side pictures only.

As an aid in estimating the height of each spray blister at each speed, grid lines are painted on either one or both sides of the seaplane. Figure 4:5 illustrates these lines on the model P5M-2 airplane. The line OX is the keel line extended while the line OZ is perpendicular to OX and

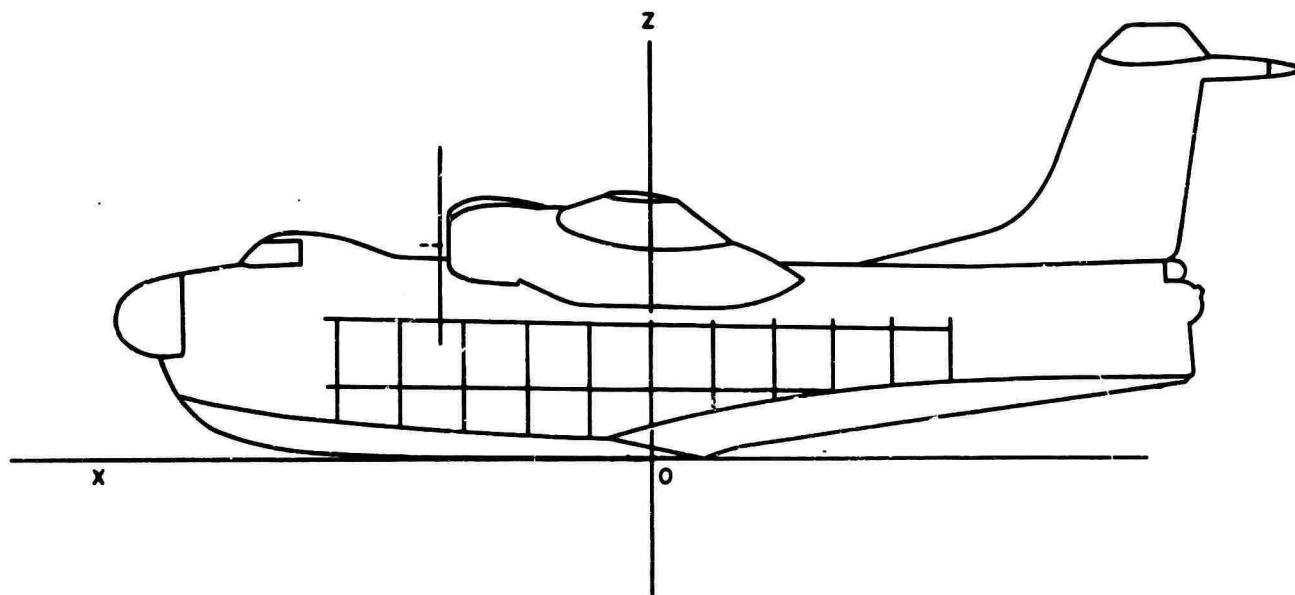


Figure 4:5

passes either through the step for a transverse step or through the step centroid for a Vee or faired Vee step.

Each square in the grid is equal to one-half the max beam width which in the case of the P5M-2 was 10 ft. The grid is usually constructed in terms of the max beam width because the dimensionless spray coefficients used in the analysis are based on the max beam width.

In the early stages of the seaplane take-off, controls are ineffective and the position of the controls is relatively unimportant. As speed increases, elevator control may be used to alter the trim angle for the same speed. Aileron control will be necessary to reduce heel angle to a minimum and rudder control will probably be required for directional control. The control position of rudder and aileron should be held as close to neutral as possible but control positions other than neutral will probably not effect results as long as a constant trim and speed can be attained.

Tests conducted to determine the mainspray envelope are most effectively accomplished in smooth water (wind 0-5 kt). The action of waves on seaplanes is principally manifested in the bow wave which varies in height and intensity as wave length and height varies. The mainspray is of course, affected by wind and wave but the extent to which the envelopes obtained in calm winds differ from those that might be obtained in rough water is usually not quantitatively determined. Spray characteristics in rough water are generally obtained by noting those portions of the airplane which receive adverse spray and the maximum wind and wave conditions which produce the adverse conditions.

Tests of hydro-skis on high performance aircraft present various additional problems in analyzing spray characteristics. In the case of hydro-ski seaplanes, spray characteristics are best analyzed during ski unporting or ski submergence using 35mm movie film. The most critical position of the take-off run from the viewpoint of spray, is that point at which the ski develops sufficient lift to break the surface of the water and support the load on the water by dynamic forces on the ski alone. This is usually the point at which the spray is highest and most dense. When the seaplane is totally supported by dynamic forces on the ski, the spray is such that for the usual range of hull trim angles it can be neglected since it falls well aft. The point at which the ski submerges during the landing runout will generally cause a high burst of spray similar to that encountered at ski unporting during take-off.

It is possible that hull type seaplanes will be, in the future, built with less hull depth than has been prevalent in the past. Reduced hull depth will possibly preclude placing grid lines on the hull. Low clearance between wing and water on high performance jet seaplanes may suppress the mainspray pattern to the extent that bow spray or spray into jet intakes may be the only significant areas of spray investigations.

#### 4.3.2.1 INSTRUMENTATION

To determine the envelope of spray blisters, the waterspeed should be used if possible since several dimensionless plots require waterspeeds. If a waterspeed indicator is unavailable then a sensitive airspeed indicator can be used and converted to waterspeed by noting the forward component of wind. A heel indicator should also be installed and can be of the simple oil-damped type. Figure 4:6 illustrates in an exaggerated manner, the correction

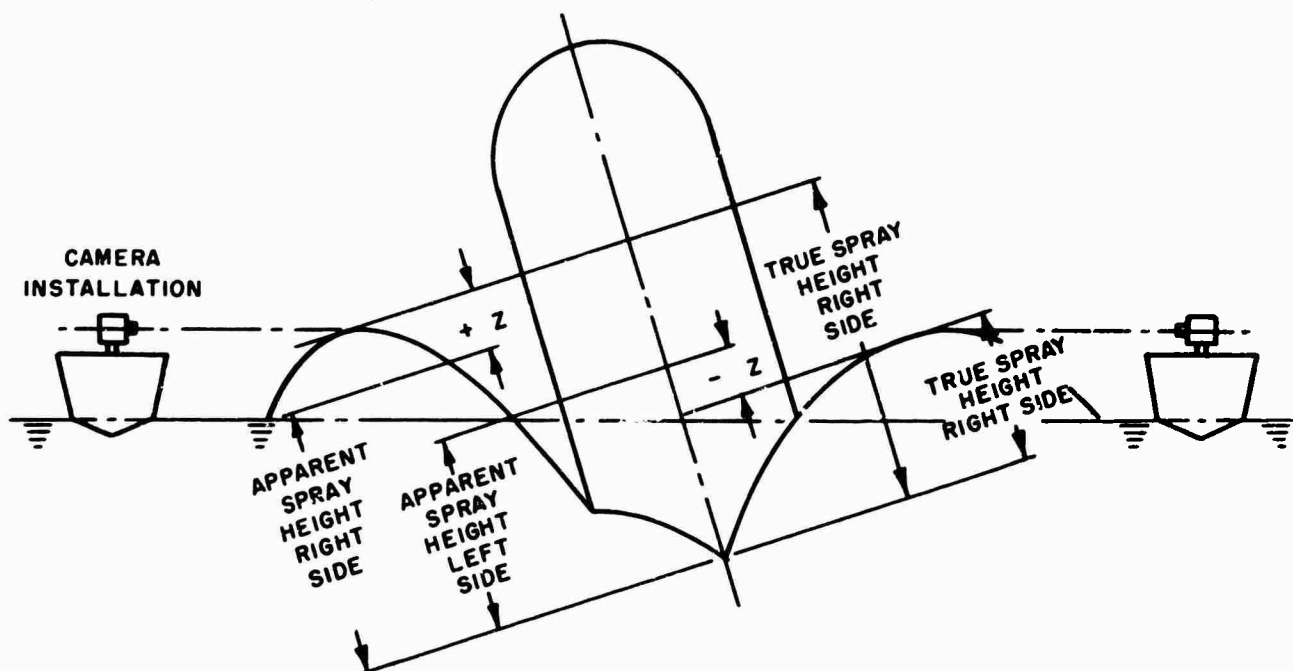


Figure 4:6

that must be applied to results obtained if the seaplane is heeled. The reason for the correction can be seen from figure 4:6 by examining the camera line-of-sight which from either side indicates only an apparent spray height and not the true spray height. Based on simple geometrical relationship, the expression for the correction of mainspray height due to heel takes the following form:

$$\delta Z = \sin \Phi (Y - b/2) \quad (4-1)$$

The distance  $Y$  which is the horizontal distance from the centerline of the seaplane to the maximum height of the spray blister can be estimated from front or overhead views. The distance  $b/2$  is the half-breadth of the seaplane hull at the hull station under consideration. Further discussion of the full scale heel correction is contained in reference (12).

The ideal recording system for the above is an oscillograph recording a continuous trace of waterspeed and heel angle. Means should also be available for marking that portion of the oscillograph traces during which the spray pattern is being photographed. Should an oscillograph not be available it is possible to obtain the same information by

means of a photopanel installation. The on-off features of the photopanel, as well as a marker feature, should be the same as those features proposed for the oscillograph installation. If the photopanel is used, a flight and run No. counter as well as a clock should be installed.

The data card maintained by the pilot, co-pilot or observer should include the following information in addition to automatic recording:

- a. Run No.
- b. RPM
- c. MAP
- d.  $V_0$
- e. Remarks on spray conditions
- f. Weight and CG
- g. Flap setting
- h. Heel angle

#### 4.3.2.2 COORDINATION

The success with which spray data is obtained, depends to a large degree on the coordination exercised during the tests. During the low speed regime (up to 30 kt), the best spray photographs are obtained by using a high speed crash boat operating such that the relative speed between seaplane and boat is as close to zero as possible. Radio communications between the boat and the seaplane are essential. If radio communications are not possible then hand signals must be planned. The signals to be used should be discussed on a briefing prior to flight. The photographer should also be briefed on the number of pictures required (usually at least two at each speed) and the best sideview to be obtained. Each film should be as completely identified as possible to facilitate film correlation.

Use of a helicopter requires further coordination. The ideal arrangement is to have overhead photos taken at the same instant the photos are taken from the crash boat. Radio communications between the test vehicle, crash boat and helicopter are a must and when the run has been stabilized, the pilot of the test vehicle broadcasts a "Mark" at which time helicopter and crash boat photographs are simultaneously taken.

At low speeds, head-on photographs can be made from the crash boat by maintaining a position just ahead of the seaplane. Although almost impossible to perform, the ideal situation would be to have side, top and front spray photographs all taken simultaneously. However, more probably a separate flight will be required for each type of view (i.e., side, top and front). At higher speeds, the problem of obtaining head-on views leads to a dangerous situation by allowing the crash boat to be approached from the rear even though, by pre-arranged signal, the crash boat veers right as the seaplane veers left. Because of the above, it may be necessary to employ tele-photo lenses for head-on views of high speed seaplanes.



#### 4.3.3 PRESENTATION OF RESULTS

For each constant speed run of the test vehicle, the photograph is analyzed and the resulting spray blister is drawn on the seaplane plan view as shown in figure 4:7.

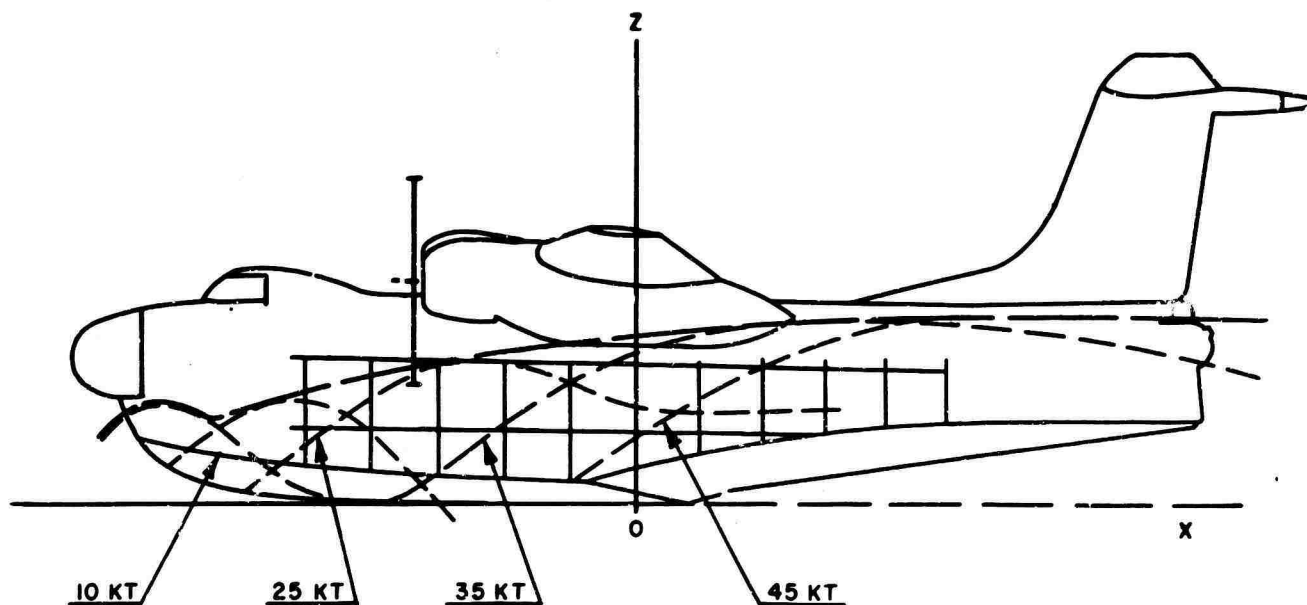


Figure 4:7

When all the spray blisters for each speed have been drawn in, an envelope may be drawn which encloses all the individual spray blisters. The resulting curve represents the main spray envelope for the gross weight under the conditions tested. The placement of the envelope is based not on the maximum height of each individual spray blister but on the point of tangency of the envelope to the individual spray blisters. The three-dimensional representation of the spray envelope is a curved surface. Figure 4:8 illustrates the curved surface where the plan view contains contour lines. The curved surface represents the blister obtained at one speed and the point of tangency of the blister in question to the envelope of all spray blisters is shown on the notation of X, Y and Z. The front and side views, naturally, show only the projection of the curved surface as a plane curve.

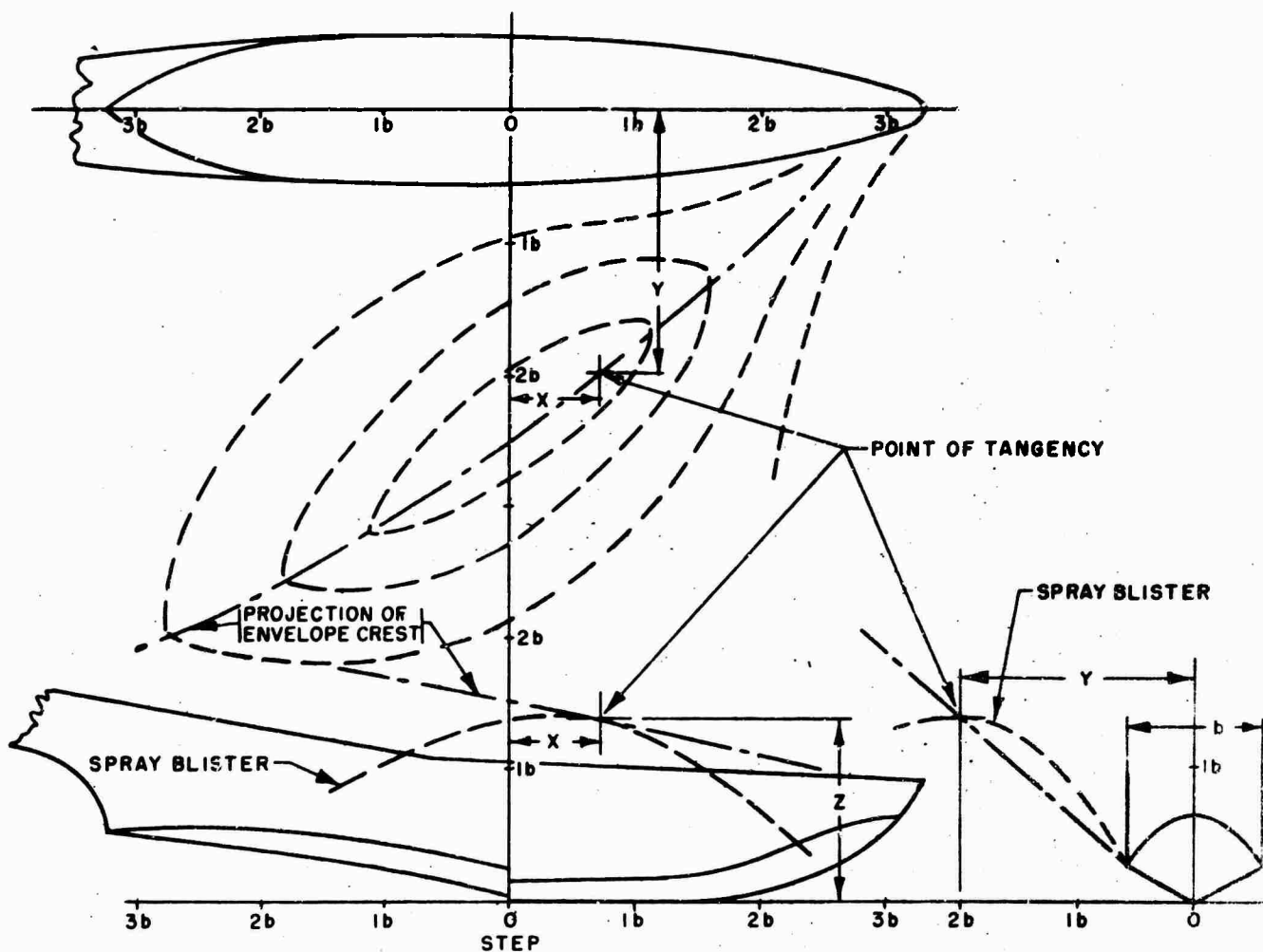


Figure 4:8

The location of the spray envelope is described by dimensionless coefficients based on maximum beam width, and the Cartesian coordinates  $X$ ,  $Y$  and  $Z$  referred to a set of axes fixed in the plane. Use of these coefficients permits comparison of hulls differing in size but of geometrically similar form. To make the coefficients applicable to hulls of different length/beam ratio, they are divided by functions of the load coefficient ( $C_{\Delta}$ ). Since spray is considered as a form of wave, the above coefficients can be presumed to be functions of the Froude number and can be plotted as such. Towing tank results by the NACA have shown that spray characteristics for a wide range of loadings are well represented by the following three curves:

$$C_X/C_{\Delta}^{1/3} \text{ VS } C_V^2/C_{\Delta}^{1/3}$$

$$C_Y/C_{\Delta}^{1/3} \text{ VS } C_V^2/C_{\Delta}^{1/3}$$

$$C_Z/C_{\Delta} \text{ VS } C_V^2/C_{\Delta}^{1/3}$$

In preparing the data in coefficient form, the point of tangency of the spray blister for each speed is located on the envelope. At each such point the speed coefficient is computed and the coordinates noted. These values are then changed to dimensionless coefficients and plotted

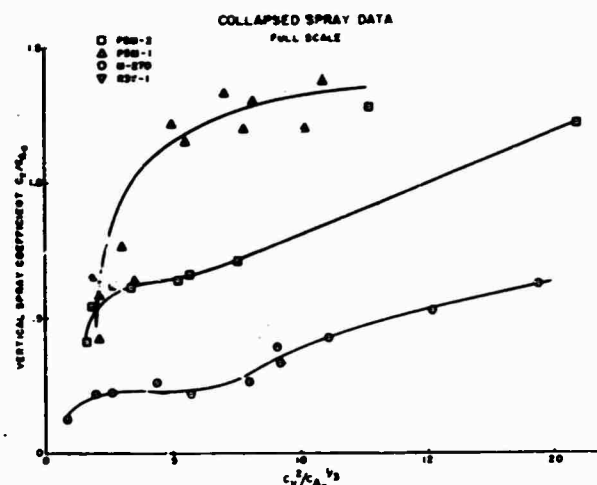


Figure 4:9

Samples of these relationships for actual seaplanes tested at the NATC are presented in figures 4:9 and 4:10. For a curve which does not contain waterspeed, a plot of  $C_X/C_{\Delta}^{1/3}$  VS  $C_Z/C_{\Delta}$  is determined as shown in figure 4:11. Data presented in the above form is valuable in comparing full scale and model results.

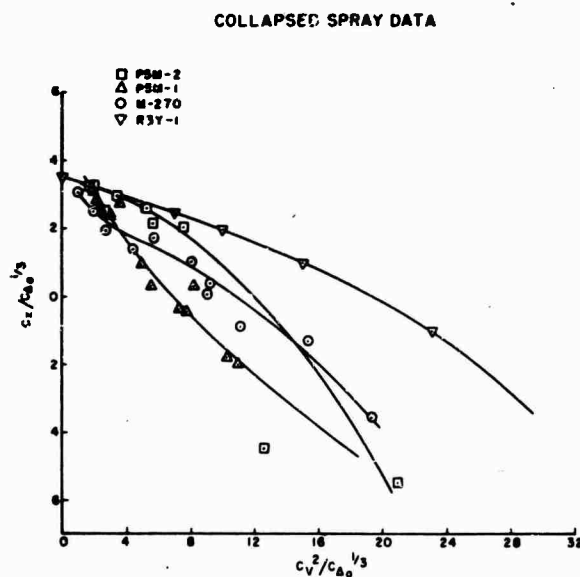


Figure 4:10

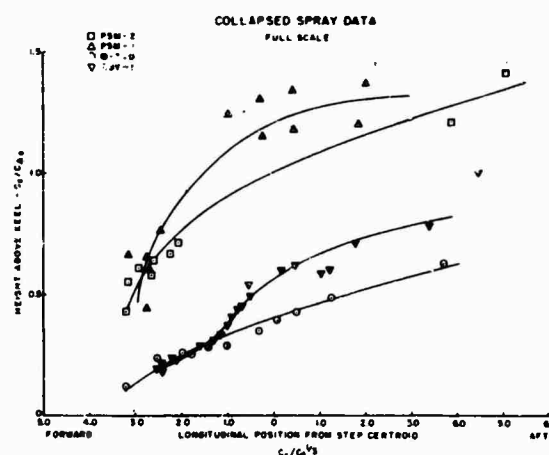


Figure 4:11

Although only coefficients of X and Z are presented, the spray coefficient of Y may be presented in a similar fashion. The difficulties of obtaining the Y dimension have already been discussed. The coefficient of load on the water  $C_{\Delta}$  is used rather than  $C_A$  (which would gradually decrease as the speed is increased based on the unloading curve) but is considered sufficiently accurate for work of this nature.

#### 4.3.4 ANALYSIS

Reference (13) contains a critique of the method used to present spray data for seaplane models and should be consulted for further information. Reference (6) contains spray characteristic curves for several type hulls and is indicative of the presentations made by towing tanks.

Figures 4:9, 4:10 and 4:11 show typical spray characteristic curves for several large hull-type seaplanes. Scatter in spray data is to be expected but one conclusion is rather evident and that is that the high length beam ratio hulls (M-270, R3Y) tend to have a flat portion in curves of  $C_Z/C_{A_0}$  VS  $C_V^2/C_{A_0}^{1/3}$ . Lower length beam ratio hulls (P5M) for the same type of curve tend to rise sharply and then flatten out.

Within the limits of accuracy of full scale testing, it is also apparent that data for several loadings will collapse to a single curve. This substantiates the reason for plotting spray data in the above manner.

The accuracy of results is highly dependent on the ability to photograph the spray, the technique used in interpreting spray photographs as well as on waterspeeds. The separation between light spray and green water is often difficult to ascertain. The hull angle at higher speeds is also of major importance and its effects must be taken into account.

There are several other ways of presenting spray data. One method would be to draw on a plot of gross weight versus speed, lines wherein the propeller arc hits the spray blister. Thus, the plot would serve to indicate limiting combinations of gross weight and speed wherein the propeller may suffer spray damage. Plots based on the clearance of the propeller arc from the spray blister show, in general, a decrease in clearance with increasing gross weight.

## 4.4 LONGITUDINAL STABILITY DURING TAKE-OFF

### 4.4.1 DISCUSSION

A seaplane may have difficulty during its take-off run even in calm water as a result of longitudinal instability. Such instability is usually manifested by "porpoising". Towing tank tests have shown that for a model restrained with freedom in heave only, the equation of motion in heave leads to a solution which indicates stable oscillations. The same thing can be shown for a model restrained with freedom in pitch only. However, the equation of motion of heave and pitch are not independent but contain "cross coupling" terms which are of the same period but not the same phase. The equations with the cross coupling terms appear in the following form:

$$d^2z/dt^2 + Z_w dz/dt + Z_\gamma z + Z_\gamma d\epsilon/dt + Z_\epsilon \epsilon = 0 \quad (4.2)$$

$$d^2\epsilon/dt^2 + M_\gamma dz/dt + M_\epsilon \epsilon - M_w dz/dt + M_\gamma z = 0 \quad (4.3)$$

and the cross coupling terms are:

$$Z_\gamma = \partial Z / \partial \dot{\gamma} \quad \text{rate of change of vertical force with angular velocity.}$$

$$Z_\epsilon = \partial Z / \partial \epsilon \quad \text{rate of change of vertical force with angle of pitch.}$$

$$M_w = \partial M / \partial \dot{w} \quad \text{rate of change of pitching moment with vertical translational velocity.}$$

$$M_\gamma = \partial M / \partial \dot{\gamma} \quad \text{rate of change of pitching moment with heave.}$$

Equation 4.2 and 4.3 are, as a matter of academic interest, two simultaneous differential equations that can be solved with the solution taking the following form:

$$z = Ae^{i\sigma_1 t} + Be^{i\sigma_2 t} + Ce^{i\sigma_3 t} + De^{i\sigma_4 t} \quad (4.4)$$

wherein the vertical coordinate  $z$  is expressed as a function of time. The quantities  $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$  and  $\sigma_4$ , which depend on the hydrodynamic and aerodynamic properties of the seaplane, indicate the rate at which oscillations increase or decay. The coefficients A, B, C, D depend upon initial conditions. A more practical application of the above equations is in the simpler solution known as "Rouths Criterion" which merely indicates whether or not accidental disturbances will decrease with time.

It has been shown in the past that accelerations and forces in the direction of planing can be neglected in the equations 4.2 and 4.3. There are, therefore, represented in the equations, only 3 stability derivatives composed of aerodynamic and hydrodynamic effects. The relative contribution to the stability derivatives of each of these of aerodynamic and hydrodynamic effects varies with speed. Due to the complexity and uncertainty of evaluating the 8 derivatives, the solution of equations 4.2 and 4.3 has been limited to contributing only a broad understanding of the porpoising phenomena. Investigations such as those reported in reference 14 have concluded that characteristics of the hull itself strongly predominate over aerodynamic characteristics and that aerodynamic changes, within permissible limits, have little effect. Of the aerodynamic changes possible, changes in the tail surface damping characteristics appear to be most important. However in making such generalities it must be remembered that changes in wing lift will produce changes in hull loading which is an important parameter in evaluating stability derivatives.

The basic forces that act on the forebody hull during planing are shown in figure 4:10a. For a given load and speed

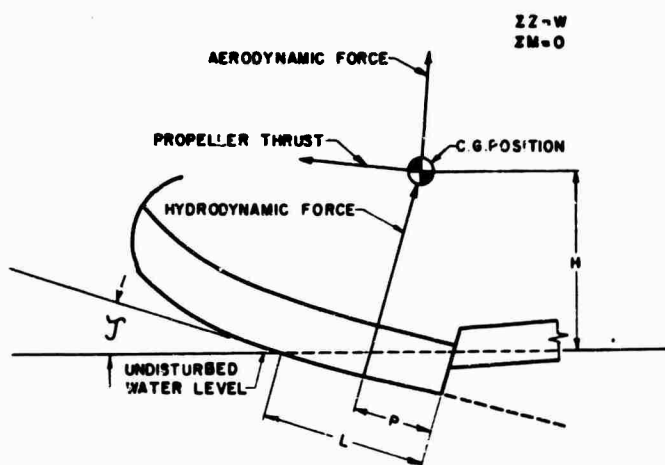


Figure 4:10a

length becomes greater, the hydrodynamic force shifts forward thereby tending to restore equilibrium planing. The above

there will be a corresponding wetted length and trim angle. When an arbitrary disturbance is imparted to the hull, steady balance of the vertical force and zero summation of moments about the CG is altered. An increase in vertical height of the CG ( $+\Delta h$ ) is accompanied by a reduction of wetted length and decrease in the hydrodynamic force. The hydrodynamic force will also shift further aft. When the hydrodynamic force is lessened, the weight tends to reduce  $\Delta h$  while at the same time producing a nose down moment since the resultant hydrodynamic force is aft of the CG. As the nose pitches down the wetted

sequence of events is the reason the equations of motion in pitch and heave are interdependant.

The same type of analysis may be envisioned for a downward displacement ( $-\Delta h$ ) wherein the wetted length increases and the hydrodynamic force shifts forward. Due to the shift forward, there will be a nose-up moment which will tend to raise the bow thereby decreasing the wetted length.

The above considerations have been simplified by assuming the forces act only on the forebody and further that no other phenomena such as suction forces have been present. Planing on two steps presents a more complicated situation since the wake of the forebody will affect the flow on the afterbody. The seaplane hull can be considered as two planing surfaces in tandem. Steady-state, two-step planing is shown in figure 4:11a, where the moments about the CG are

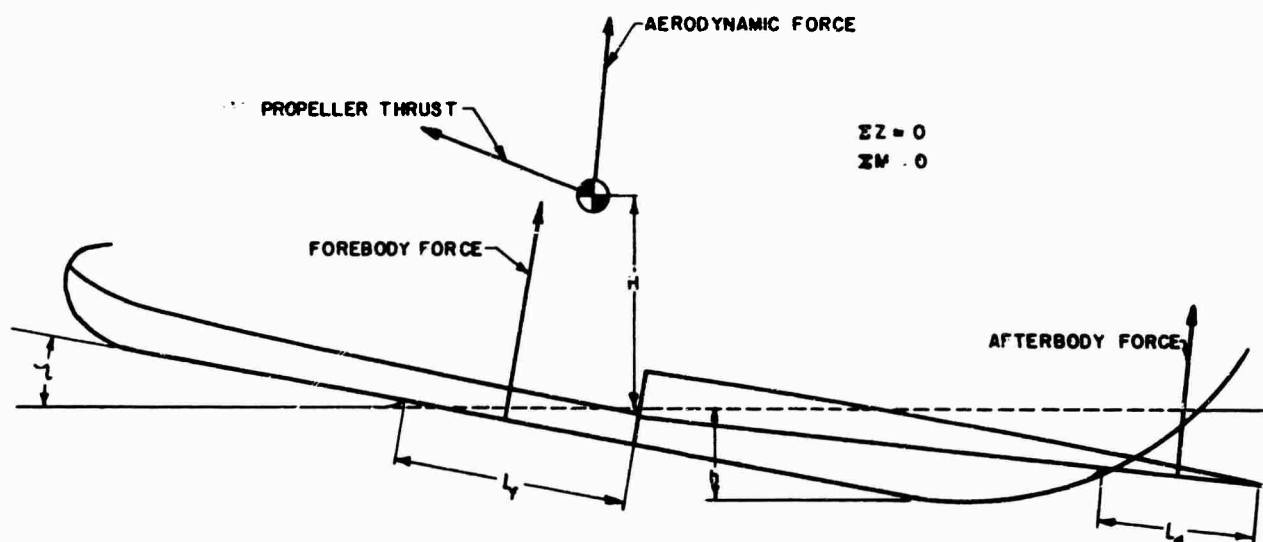


Figure 4:11a

zero and the vertical force is equal to the weight. Hydrodynamic lift is produced by the downward deflection of water and the depth of the wave ( $h$ ) will depend on the forebody load. A decrease in draft (i.e. upward heave) reduces the hydrodynamic force as well as shifts the point of application further aft. Due to the reduction in wetted length, the wake depth ( $h$ ) decreases and the wetted length and the force on the afterbody are thereby increased. With the decreased hydrodynamic force on the forebody, the total force becomes less than the weight and the hull is given a downward acceleration. A diving moment is simultaneously generated. An oscillatory motion is thereby generated by the shifting of resultant forces on the forebody and afterbody and the variation in magnitude of these forces. The above



discussion has been concerned with the displacement from steady state caused by a variation in heave. A similar sequence of events can be occasioned by a variation in trim or a combination of heave and trim which in actual practice is more likely to be the case.

The majority of information in existence on longitudinal stability has been gleaned from towing tank tests of scale models. The sequence of events described above has been confirmed from analyses of many records of trim, heave, pitching moment and wetted area photographs. In the smooth water model tests, conditions can be much more carefully controlled than in full scale testing. A further advantage of model testing is that the tests in the towing tank can be carried out to the limit without results any more serious than loss of the model. This makes it possible to observe whether or not model oscillations will damp, sustain or amplify when the oscillations are carried beyond the limits set. In sea-plane motion analysis, there are two areas of longitudinal instability. One occurs at relatively high trim angles and is referred to as the upper limit while the other occurs at relative low trim angles and is referred to as the lower limit. All other things being equal, the exact location of the trim angle limits is frequently one of definition. Arbitrarily, a two degree double amplitude porpoising defines the limit. The degree of instability should be defined since the transition from damped to neutral to divergent motion may occur over a wide or narrow band. The line which is used to define the upper or lower limit of stability is more properly characterized as a band of varying width within which exists an area of potential instability. Within this area the motion may be oscillatory, steady and undamped but non-divergent as well as non-oscillatory and steady. The upper limit band is bounded by an "upper limit trim increasing" which is greater than the "upper limit trim decreasing". The "upper limit trim decreasing" can be considered the result of a dynamic effect predicated on the application of pilot control to the elevator in order to reduce the existent trim to a lower value. In other words, it is a dynamic effect prevalent in full scale testing and not usually encountered in towing tank work under fixed-elevator conditions.

The same type of band exists at the lower limit. Despite the possibility of actually obtaining both the upper and lower portions of the band under tank-controlled conditions, it is accepted practice to establish a single limit based on a 2° double amplitude oscillatory motion. Such a single line

is quite practical since in full-scale testing it is all that can be obtained. The difficulty in determining full-scale limits can frequently be traced to the dynamic effects existent within the band of instability which leads to the scatter of data which in turn affects reproducibility of results.

There is one recent concept in the study of hydrodynamic longitudinal stability, first investigated by the British in their towing tank work, that should be discussed. A large British seaplane showed satisfactory trim limits of stability in its towing tank tests. However, when the full scale article was tested, during one particular run in calm water, the seaplane intercepted the wake of a small boat, and went into a violent uncontrolled porpoise. The seaplane was lost. The British have taken the viewpoint that in model work it can be illustrated that a disturbance imparted to the model will change the trim limits of stability. For instance if the model while running at a given speed and trim angle is given a disturbance, such as a change in trim or heave, the stability limits will differ from those limits obtained under ordinary conditions. Reference 15 contains a discussion and results of imparting initial disturbances to a model running under equilibrium conditions. The discussion centers about the band of instability which makes up the upper limit and the dynamic effects prevalent when the seaplane enters the band. This band in the upper limit is bounded by an "upper limit trim increasing" and an "upper limit trim decreasing" which is alternately referred to as the secondary limit. No definite conclusion was made except that the disturbance method did tend to define the upper limit trim decreasing or secondary limit and that the magnitude of the disturbance became less important as the trim decreased.

The British have continued to include undisturbed and disturbed limits in their model testing. However, in the United States, the determination of the trim limits of stability using the disturbed technique has not gained widespread usage. The difficulties of applying a disturbance of satisfactory magnitude and correlation with full-scale results are such that the problem still remains unsolved.

#### 4.4.2 TEST PROCEDURE

In the towing tank, constant speed, fixed trim runs are relatively easy. In full scale testing such is not the case and fixed-elevator accelerated take-off runs are easier. The elevator angle is held constant and the seaplane is accelerated to take-off using rated take-off power. During the run, the longitudinal behavior is noted with particular reference to porpoising both during the run and at take-off. The elevator angle is varied by suitable increments for each take-off run until an elevator range is established within which porpoise-free take-offs may be made. Tests are usually conducted in light winds (5 kt or less) with runs under identical conditions being made upwind and downwind in order to cancel existing wind effects. Runs to determine longitudinal stability in high winds are usually qualitative in nature.

Prior to the commencement of tests or at some point during the conduct of tests, the acceptable limits of elevator deflection for satisfactory take-off must be determined. The usual limits are set at  $2^\circ$  double amplitude. This means that during the take-off run at a constant elevator setting if the trim angle registers a  $2^\circ$  or more spread in trim angle oscillation, the run is considered unstable. Unfortunately even this arbitrary demarcation is conditioned by hull reaction. For instance one may ask what happens when the  $2^\circ$  oscillation is encountered. The hull may sustain its oscillation, or the oscillation may decrease or increase. That is, the motion may be divergent or convergent. There is no rigid rule that specifies the " $2^\circ$  limit" as being the limit of pilot controllability or comfort. In setting the limit for satisfactory take-off, the best course of action is to carefully approach from the known stable region those elevator angles specified by the contractor.

During the conduct of hydrodynamic longitudinal stability the following items should be recorded:

- a. Wind direction and velocity
- b. MAP
- c. RPM
- d. BHP

- e. Elevator angle
- f. Type of porpoising
- g. Amplitude of porpoising
- h. Speed and trim at onset of porpoising
- i. Direction of run
- j. Flap setting
- k. Gross weight and CG
- l. Speed and trim at take-off

These items should be recorded even though automatic recording is being used. The point at which recording is begun depends on the area of investigation and the extent of information required. Take-off runs generally require 45-60 sec. When using an oscillograph, several such runs will result in miles of recorded data. This mass of recorded data makes analysis tedious and is one reason why qualitative tests are preferred in seaplane testing.

#### 4.4.2.1 INSTRUMENTATION

Figure 4:1 indicates the data desired for longitudinal stability tests. In the event that a simple test program is desired, instrumentation may be limited to the following:

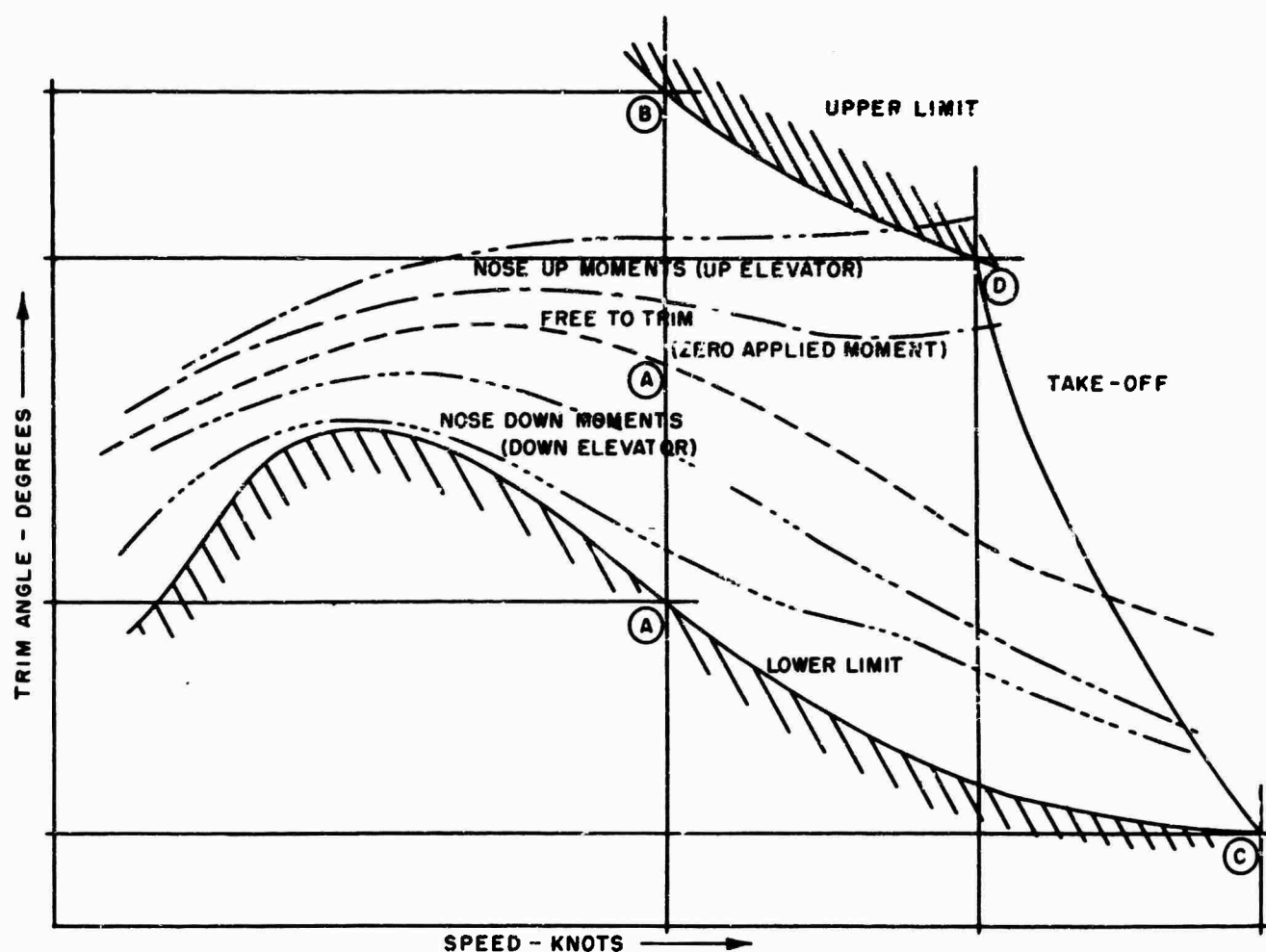
- a. Trim indicator - NACA visual or Gianinni vertical gyro.
- b. Elevator position indicator.
- c. Sensitive airspeed indicator.

As is the case in most of the hydrodynamic tests, the oscillograph or magnetic tape are preferred for automatic recording. Continuous traces of elevator position, trim angle and waterspeed supply the needed information in graphical form. The Gianinni vertical gyro eliminates the guess work of optical systems such as the NACA visual trim indicator. Satisfactory waterspeed or airspeed recording is dependent on the installation and the pressure transducers used to record on the oscillograph.

The take-off point is determined from the drop in waterspeed and the change in attitude and acceleration after leaving the water. To eliminate guess work it is advisable to incorporate a marker button which produces a mark on the data trace when actuated. When the hull leaves the water, the co-pilot actuates the trace marker. The positive trace marking makes it easy to spot the take-off point on the oscillograph record.

#### 4.4.3 PRESENTATION OF RESULTS

Figure 4:12 illustrates the type of chart that is usually obtained as the result of towing tank test on models. The range of the chart varies from zero to getaway velocity



REPRESENTATIVE LONGITUDINAL STABILITY LIMITS

Figure 4:12

and shows where both lower and upper limit porpoising will be encountered. The stability limits shown on the figure represent  $2^\circ$  double amplitude porpoising. The free-to-trim track is usually obtained only in the towing tank and represents the path that the hull or seaplane will take with respect to trim angle and speed when the moments acting on the seaplane are zero. As positive or negative moments are added to the hull a path is traced which is different

from the free-to-trim track. These curves of the hull path with various positive and negative moments applied are also shown in figure 4:12. The moments referred to above are constant during the accelerated runs from zero to getaway.

The limits established in figure 4:12 can be determined by constant speed runs as well as by accelerated runs. If, a constant speed is selected and a line drawn perpendicular to the speed scale, the speed line will intersect the lower limit at the point A, the upper limit at the point B, and the free-to-trim track at the point A. The model, balanced for a given CG location, is allowed to seek its own trim with zero applied moment. The speed and trim at which the forces on the model are in balance will occur at the point A. As nose down moments are applied at the same speed, the running trim will be less and less until, at the point A, 2° double amplitude porpoising is encountered which is the lower limit by definition. As nose-up moments are applied, the constant speed trim will gradually increase until upper limit porpoising is encountered at point B. By gradually increasing the speed of each run, the stability limits from zero to getaway speed are determined. The curve D - C represents take-off conditions, and in model work is based on maximum lift coefficient of the complete model. It is called the take-off curve.

The type of curves represented by figure 4:12 are obtained in full scale testing by using several constant elevator angles during accelerated take-off runs. The moment curves just discussed are not identical to curves obtained during constant elevator runs since the moment contributed by the tail is a function of tail lift which will change with changes in speed. However, a plot of fixed elevator as shown in figure 4:13 is extremely valuable in illustrating the seaplanes performance from zero speed to getaway when using constant elevator position.

The areas of instability, as defined by the porpoising limit curves are difficult to obtain by constant speed runs. Time histories of accelerated runs at constant elevator position are analyzed to determine areas of instability by noting changes in trim angle. The upper and lower limits of figure 26 were obtained in just such a way. The exact location of the upper and lower limit is subject to error since the effect of high longitudinal acceleration would be to cause the seaplane to pass through areas of instability before any adverse effects could be manifested.

## HYDRODYNAMIC LONGITUDINAL STABILITY

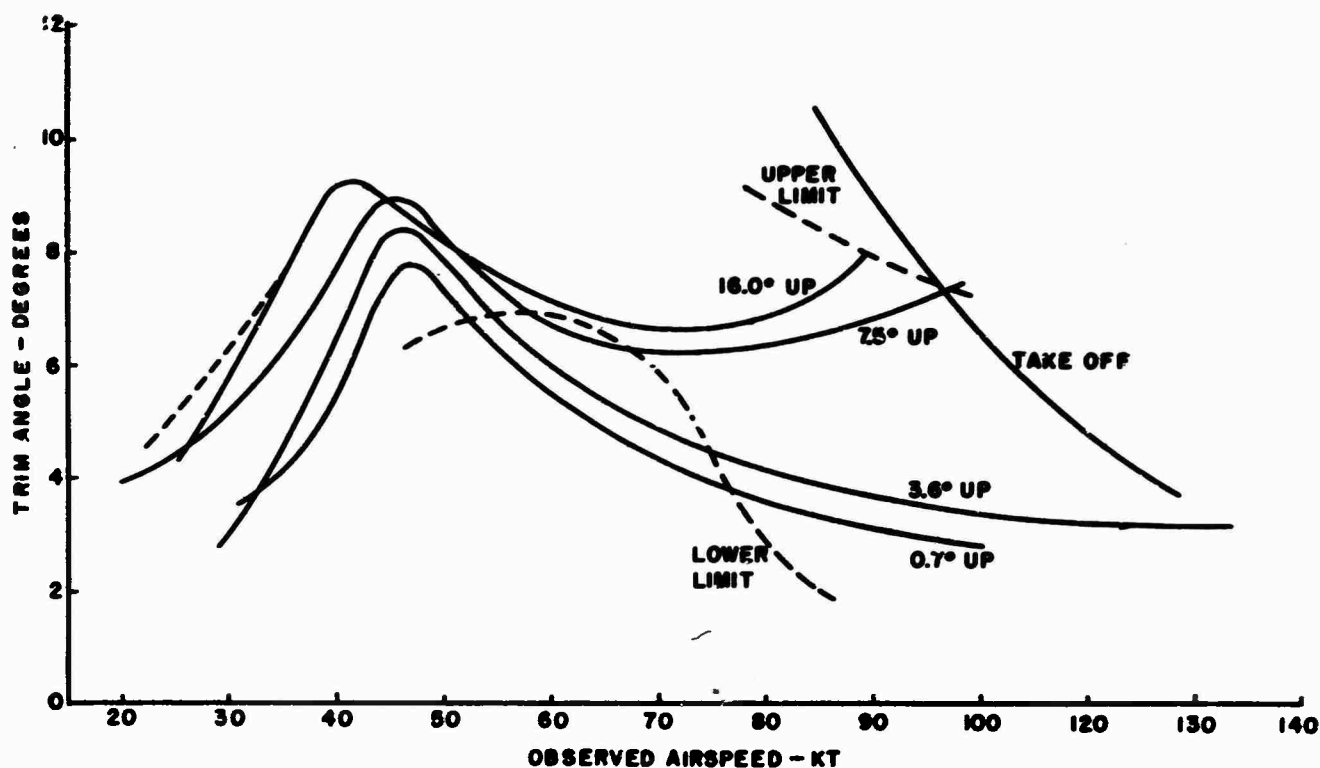


Figure 4:13

The take-off curve is readily plotted by noting the speed and trim at which the seaplane flies off the water. As simple as the curve is, the repeatability becomes increasingly difficult as the wind increases. Maximum repeatability can only be obtained when the winds are calm.

By varying gross weight, flap setting and CG position the take-off performance is presented in terms of the take-off curve as shown in figure 4:14. Figure 4:14 is a representative plot for one gross weight and illustrates the effect of flaps. Accumulative seaplane testing has shown that there is no detectable difference in the take-off curve with variations in the position of CG for a constant flap setting. Change occurs in the amount of elevator necessary to maintain a given hull trim angle and speed.

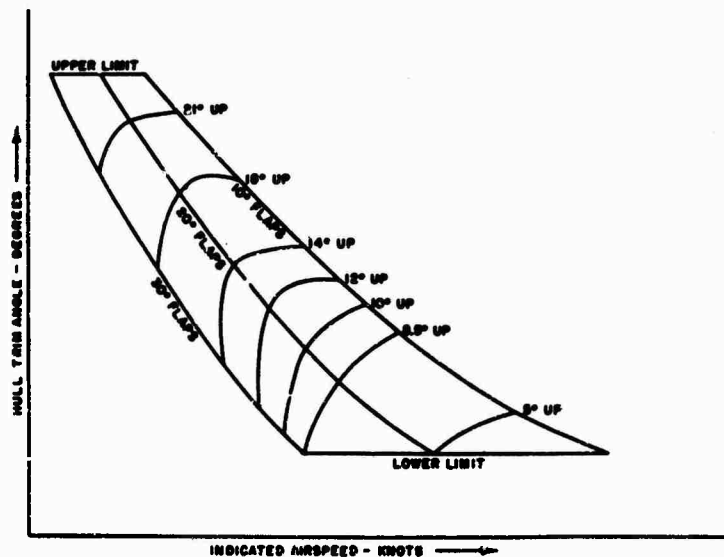


Figure 4:14



The change in elevator angle for variation in flap position and CG is shown in figure 4:15 and is another

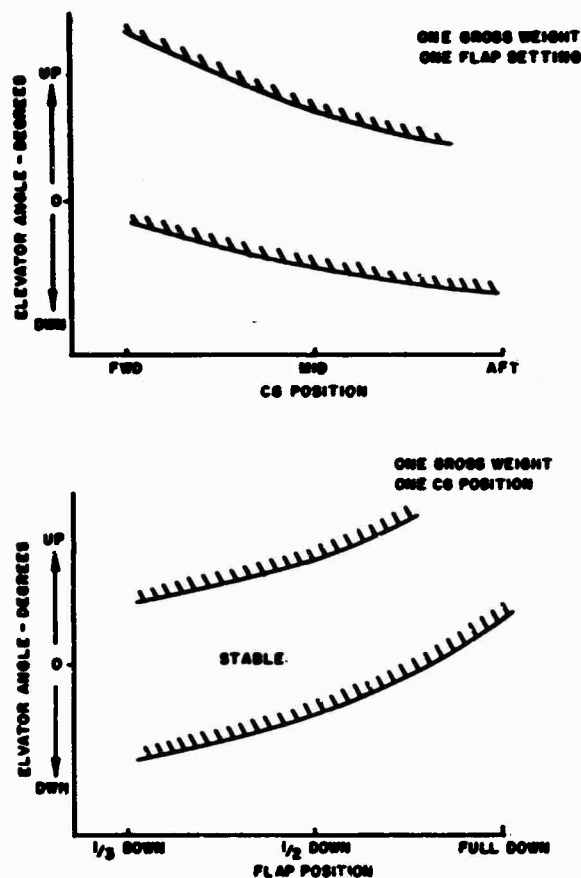


Figure 4:15

method of presenting sea-plane performance at take-off. For one gross weight and flap setting the curve shows the range of stable take-off for elevator angle versus CG position. An alternate plot is also shown for one gross weight and one CG position which shows the elevator range of stable take-off for elevator angle versus flap deflection. The principal disadvantage of figure 4:15 is that the curves represent only the conditions at take-off and do not indicate the possible instability encountered in performance prior to take-off. A combination of the above two plots would require three dimensions and could be presented for one gross weight as shown in figure 4:16.

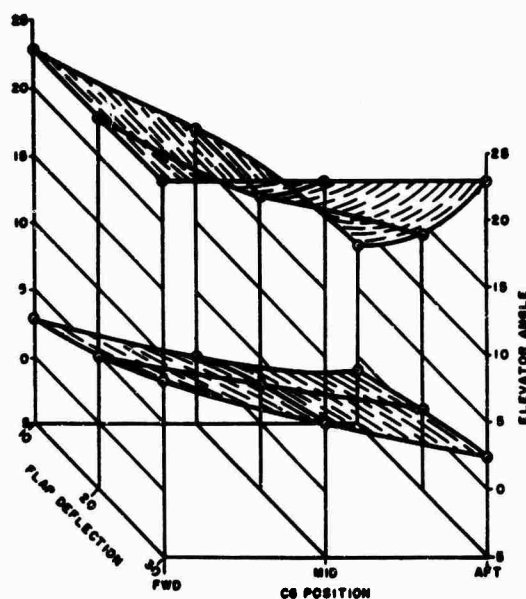


Figure 4:16

#### 4.4.4 ANALYSIS

The type of curves shown in figures 4:14, 4:15 and 4:16 are slightly misleading in that they refer only to take-off characteristics. Figure 4:13 is much more realistic in that potential porpoising can be avoided prior to reaching getaway speed by holding the amount of elevator angle necessary to stay out of unstable areas during the entire take-off run.

When graphs such as figure 4:12 are constructed from model data obtained during constant speed runs, results may be less optimistic when compared with full scale accelerated take-off runs. Part of this difference is due to longitudinal acceleration. With a large amount of longitudinal accelerations, areas of instability can be traversed before the instability can manifest itself.

The actual upper and lower limits determined from tests at NATC may be positioned from considerations other than 2° double amplitude porpoising. For instance at the high speed end of the take-off curve, the lower limit may be set, not because the airplane will porpoise, but because the hull is at such a low trim angle that it will not accelerate to getaway speed. Also at such low trim angles there is a distinct possibility of encountering a diving moment of such magnitude that the loss of the seaplane will occur. This low limit is difficult to determine except by feel. The upper limit may also be arbitrarily set at some trim angle above which unusual attitudes occur thereby endangering the seaplane. In long afterbody hulls it is possible to plane on the afterbody alone at trim angles greater than the sternpost angle. At these high trim angles the acceleration is poor, there is insufficient hull planing lift and the drag force on the afterbody is excessive. The resulting motion is similar to porpoising except that the interaction of forces is aerodynamic and hydrodynamic. Hull attitudes produced by this motion are extreme and may become uncontrollable if coupled with external forces such as waves or boat wakes.

The take-off curves of figure 4:14 are difficult to reproduce in anything greater than 5 kt winds, and should not be attempted. The basic curve for take-off appears to depend only on the gross weight and flap setting, assuming that there are no changes to the hull form. A change in CG position will not change the basic curve for

the same flap setting but the lines of constant elevators setting super-imposed on the take-off curve will change. Should the plotted take-off data appear erratic the data can be corrected by plotting the hull trim angle versus the reciprocal squared of the airspeed ( $1/V_o^2$ ). This is basically the lift curve and should result in a straight line. A measure of the accuracy of the data is its proximity to the straight line.

## 4.5 LONGITUDINAL STABILITY DURING LANDING

### 4.5.1 DISCUSSION

The stability of a seaplane during landing is similar to the stability during a take-off except that the sequence of events is reversed. During landing operations bouncing, skipping or other indications of instability may be manifested. Common procedure has been to represent such instability by what is termed the "skipping behavior" of seaplane hulls. The term skipping is generally applied to describe the phenomena of the seaplane leaving the water after having made initial contact. The skipping phenomena is different from "bouncing" which is a manifestation principally encountered during "impact" or high rate of sink operations. The difference is not clear cut. The "bounce" is usually occasioned by high trim angles, excessive speeds, and/or high sink rates in which hydrodynamic lift is generated on the hull to a point where it becomes excessive and the hull is lifted back out of the water after having absorbed the energy of impact.

Skipping is essentially a hydrodynamic phenomena which occurs during landing and is associated with conditions whereby the forebody carries most of the waterborne load. At the same time skipping occurs, a large amount of water washes over the afterbody bottom. Skipping is dangerous because the act of leaving the water occurs below flying speeds and may result in the seaplane becoming airborne without sufficient speed for controllability. There is no trim range above or below which skipping can be separated from "bounce". However skipping is generally thought to occur at lower combinations of airspeed, trim and/or glide path than bouncing. Skipping is not usually associated with outside phenomena acting on the seaplane such as waves or boat wakes.

In the phenomena of skipping, the sequence of events is generally as follows: Prior to contact with the water, an airflow pattern exists on the entire bottom of the hull. At the instant of contact, the airflow is interrupted at the step and a suction is generated on the afterbody by the inertia and entrainment of air brought about by water moving in close proximity to the afterbody. The developed suction force acts over a large surface to produce a downward force and a stalling moment. The downward force produces excessive hydrodynamic lift. The rapidly developing

wake is deflected downward breaking suction on the afterbody. With excessive forebody lift and afterbody suction eliminated, the hull will rise clear of the water. These events occur in rapid sequence occupying a fraction of a second.

The possibility of skipping is enhanced under conditions where the afterbody is relatively horizontal to the undisturbed water level. With an average sternpost angle of  $9^\circ$ , a level afterbody would require the trim angle to be  $9^\circ$ . This angle is close to upper limit porpoising for those hulls that exhibit upper limit porpoising.

In practical operations, it is desirable to land in a steady gradually descending approach at high trims in order to obtain lower landing speeds. It is this high trim attitude that leads to the conclusion that there is a strong similarity between skipping and upper-limit porpoising. On the other hand, low angle, high speed landings are sometimes made with excessive airspeeds such that a mild "skip" without trim changes can be encountered. It has been concluded therefore, that upper-limit porpoising and skipping are related in such a manner that skipping can be considered upper-limit porpoising in which the hull leaves the water in a cyclic pattern. There is a tendency for the cyclic pattern of skipping to involve changes of heave primarily, and changes of trim only secondarily. This statement does not appear quite the same for upper-limit porpoising. At high speeds and small waterborne loads, the hull may leave the water for some part of each cycle during upper-limit porpoising but separation from the water is not generally a criterion for upper-limit porpoising. During upper-limit porpoising under conditions of low speeds and heavy loads, the hull does not leave the water. Reference 15 contains a discussion of the landing phenomena of skipping and bouncing and their relation to upper-limit porpoising.

Recent seaplane hull types have been relatively free from skipping and at the same time singularly free from ordinary upper-limit porpoising. This is further evidence of the inter-relation between upper-limit porpoising and skipping.

#### 4.5.2 TEST PROCEDURE

Tests for the determination of longitudinal stability during landing consists of making landings at various combinations of trim angle and airspeed. During each landing a fixed elevator setting is maintained, the constant glide path angle should be small and no pitch or acceleration should be induced prior to water contact. Throughout these tests, hull behavior subsequent to initial water contact is of prime importance.

During landing tests, rate of descent should be varied from 200 fps, to duplicate the operational night landing technique and investigate heaving characteristics, to landings at 50 fps to investigate skipping characteristics at low trim angles. Each sink rate is established by a fixed power setting and elevator angle. Power may be cut, if desired, after initial touchdown.

Landing tests should be initiated at the approach attitude associated with the best flight handling characteristics of the airplane. The associated trim angle should be recorded. This trim angle then provides the norm from which deviations can be made for test purposes. Subsequent landings are made at lesser trim angles until the minimum safe trim angle, as determined from take-off tests, is attained. This series of landings are performed with the same flap settings, center-of-gravity location and gross weight.

Ideally a series of tests are performed after only one parameter has been changed. Practically the tests are performed at the flap setting, CG or weight that is believed to be the most critical from model tank tests. During a limited test scope, it is recommended the investigation be made during landings at the highest gross weight associated with the maximum aft CG position and fully deflected landing flaps. The technique to be used by a contractor in demonstrating these qualities are contained in MIL-D-8708 paragraph 3.7.4.

The following data should be recorded during landing stability tests:

RPM  
 $V_0$  at contact  
Trim angle at contact

Elevator angle  
Flap settings  
Number of skips  
Wind velocity  
Wave height and length  
Gross weight and CG position

### 4.5.3 PRESENTATION OF RESULTS

Figure 4:17 illustrates typical curves which may be used to show the landing stability of any seaplane. In full scale testing, the determination of the glide path angle requires high speed camera coverage external to the airplane. Trim angle and airspeed at touchdown are recorded at the moment of touchdown. Information on trim and airspeed after touchdown requires continuous film or oscillograph recording in the airplane.

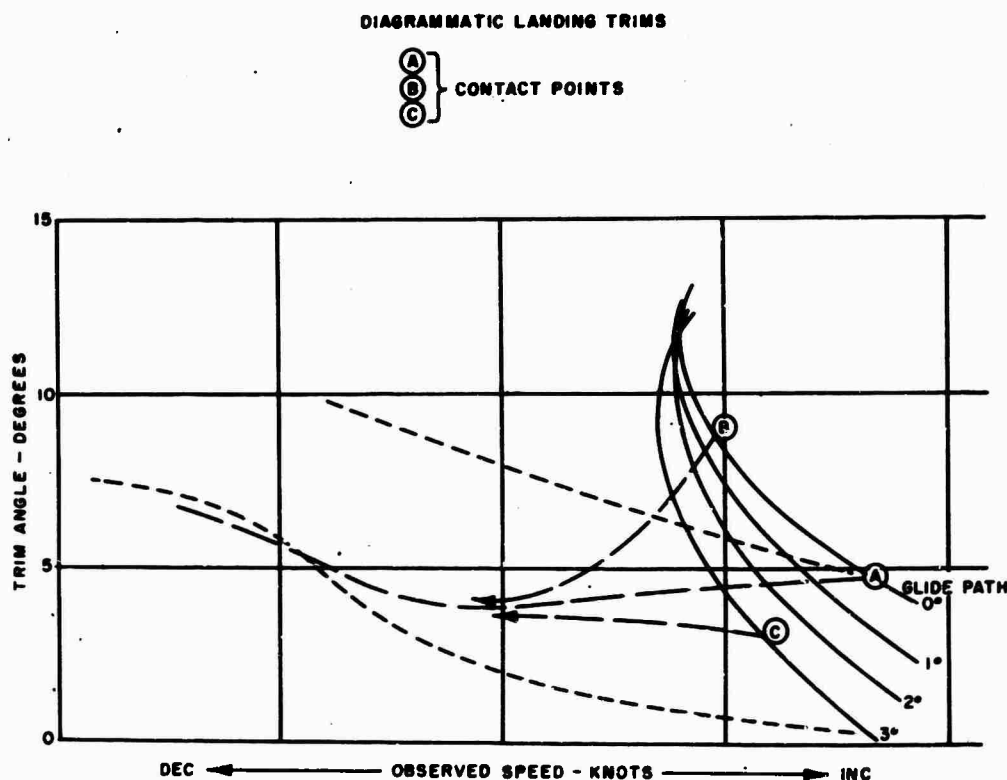


Figure 4:17

Since the determination of skipping tendencies is essentially a statistical study, the results may be presented as shown in figure 4:18, (a) through (d). Landings made at one flap setting, CG location and gross weight may be combined as in figure 4:18 (d) for skip free landing trims versus CG location. Figure 4:18(c) is similar to the take-off curve but with reduced power and is identical to the landing curves in figure 4:17 for constant glide path. One particular presentation is not preferred. The requirement is that the information obtained be presented in a manner that leaves no doubt as to the seaplanes performance.



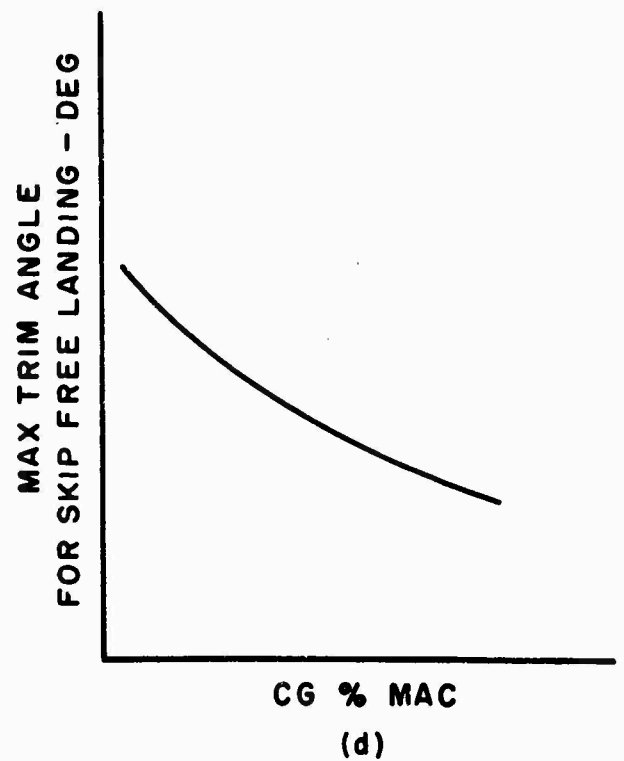
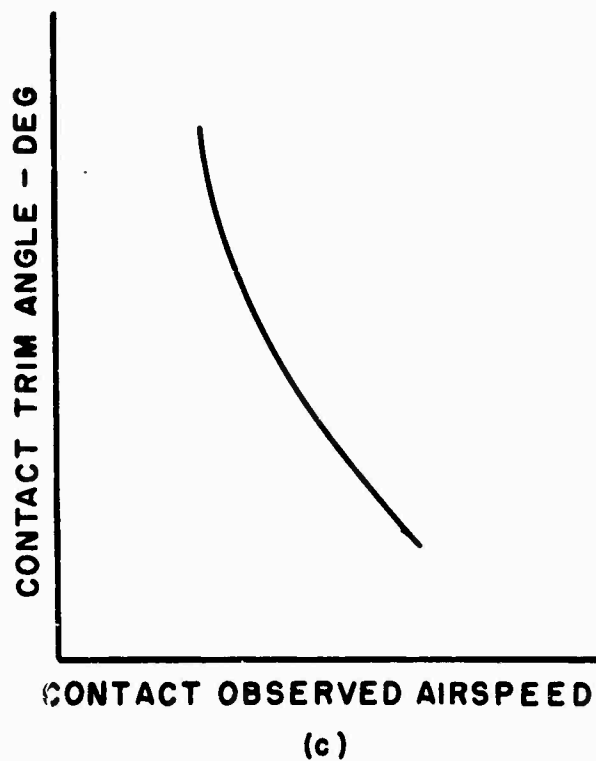
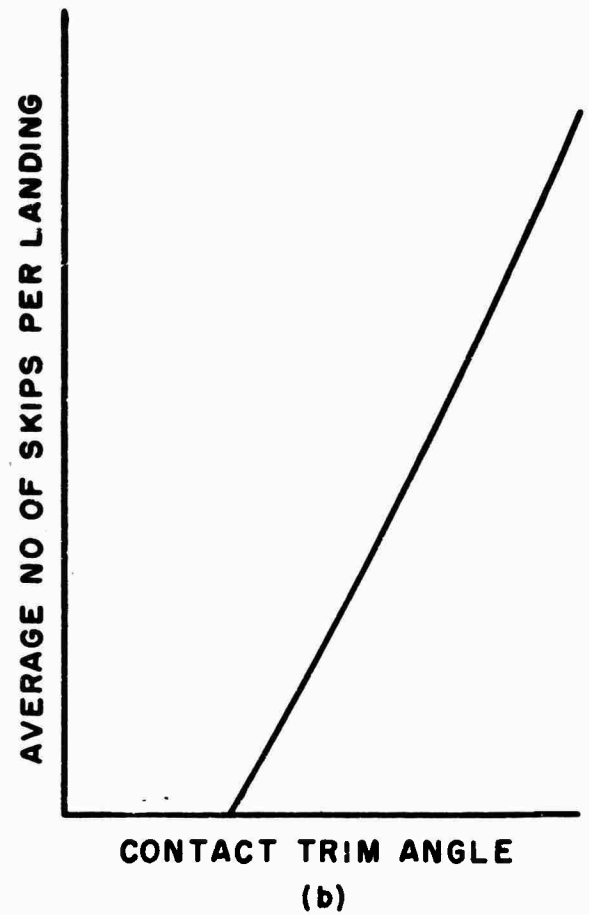
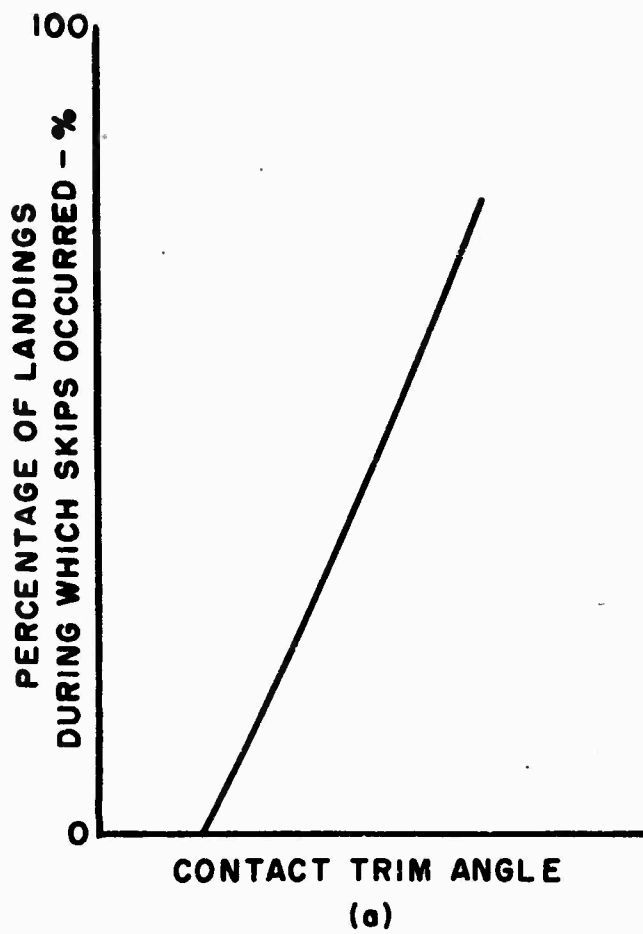


Figure 4:18

#### 4.5.4 ANALYSIS

In general it may be stated that landing stability is a function of upper-limit porpoising characteristics, the position of the free-to-trim track and the time factor governing speed and trim changes during deceleration. Landing speed, trim, vertical speed and approach techniques are functions of upper-limit porpoising characteristics.

Figure 4:17 illustrates three possible landing combinations. In landing A the glide path is zero with a moderate trim angle and high landing speed. Provided speed is not excessive skipping under these conditions will depend upon the length of time (a function of the deceleration characteristics) that it takes the hull to pass through the area of instability.

In landing B, the glide path is the same but the trim is high and the speed is low. The hull is being "dragged in". Due to the high trim angle it is anticipated that deceleration effects will cause the hull to pass through the unstable area more quickly than in landing A. In landing C the glide path is highest while the trim is lowest with a medium airspeed. A stable landing under these conditions is reasonably assured since the landing track remains clear of unstable areas.

#### 4.6 LONGITUDINAL CONTROL

During landings and take-offs, the test pilot should qualitatively determine the suitability of the seaplane longitudinal control. Quantitative data obtained under conditions of various weight, CG positions and flap setting will generally indicate the degree of restrictions that must be imposed during take-off and landing operations. For instance, at the most forward CG position and with flaps fully deflected, the data may indicate that insufficient elevator is available to remain clear of lower limit porpoising and consequently restrictions would be imposed.

To adequately comment on longitudinal control the following qualitative questions must be answered by the pilot:

- a. Is control adequate to get out of unstable areas (entered either inadvertently or induced by outside disturbances)?
- b. Does water impingement on the elevator control affect controllability? If so, to what degree?
- c. Under certain conditions does the hull tend to assume any unusual angles, and are these angles easy or difficult to maintain or change?
- d. Is the seaplane controllable when influenced by ground effect?
- e. During landing or take-off is there any excessive transitional pitch-up or pitch-down?
- f. Is there excessive pitch-up or pitch-down due to the operation of auxiliary control devices (landing flaps, hydro-flaps)?
- g. What effect does crew or CG shift have on longitudinal control?

The British have devised a method of presenting elevator effectiveness that appears to be suited to comparing elevator effectiveness of different seaplanes. Briefly, elevator effectiveness is defined as the rate of change of hull trim angle with changes of elevator deflection. Figure 4:19 shows the basic plot for a given flap deflection

gross weight and CG position. The information in this plot is gleaned from time histories of fixed elevator runs such as contained in figure 4:13. From figure 4:13 a vertical line may be drawn at a constant speed coefficient. Along this line information is obtained from which a plot of elevator angle versus hull trim angle for constant speed coefficient is constructed. This procedure is continued for as many different speed coefficients as may be required. Figure 4:19 is then constructed for each speed coefficient.

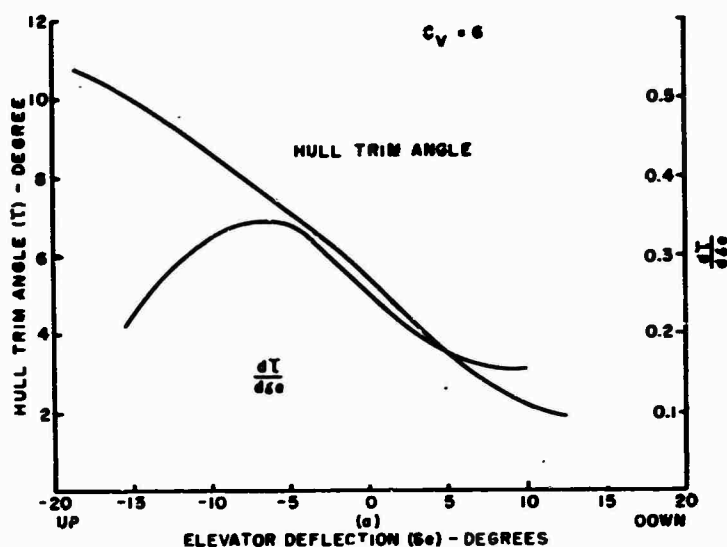


Figure 4:19

By measuring the slope of the curve of hull trim angle versus elevator angle, a curve of  $dT/d\delta_e$  versus elevator deflection can be plotted. In order to plot figure 4:20

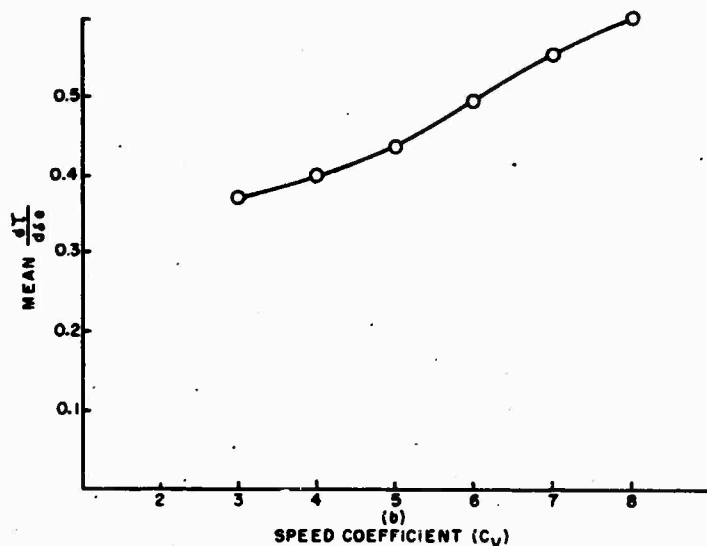


Figure 4:20

of the rate of change of elevator effectiveness with a change in speed coefficient for a given gross weight, CG position and flap setting. Figure 4:20 is an ideal plot for comparing directly the elevator effectiveness of various seaplanes.

an average or mean value of  $dT/d\delta_e$  is computed for each plot of  $dT/d\delta_e$  at constant speed coefficient. This average value may be obtained in many ways the accuracy of which will depend on the particular seaplane being tested. When average values have been established for each speed coefficient the curve in figure 4:20 is plotted. The curve is then a measure

## 4.7 DIRECTIONAL STABILITY AND CONTROL

### 4.7.1 DISCUSSION

Directional stability may be grouped into three phases:

- a. During taxiing (including maneuvering)
- b. Pre-hump stability
- c. Take-off stability at post-hump speeds

Directional stability during taxiing is measured during maneuverability testing discussed in Section 3.2. The present section is limited to pre-hump and post-hump directional stability and is equally applicable to take-off and landing.

At low taxi speeds the hull is a displacement body with draft deeper forward than aft. A wind force causes a drift or yaw angle to form. The resultant reaction of water force acts on the forebody forward of the CG position thereby producing a de-stabilizing moment and increasing the initial yaw angle. The wind force acting on the tail surface adds an additional de-stabilizing moment which, coupled with the forebody de-stabilizing moment, forces the seaplane to turn into the wind or weathercock.

The forebody of a seaplane hull is inherently unstable and the seaplane hull requires the afterbody to supply stabilizing moments. Older seaplanes of the PHM type were quite susceptible to weather-cocking. However, recent seaplane advancements have produced much higher length-beam ratio hulls which do not readily weathercock but being more hydrodynamically stable will tend to decrease the yaw angle produced by the wind thereby turning out of the wind. The degree to which this occurs depends on the forward velocity.

Figures 4:21, 4:22 and 4:23 illustrate typical model results for three different speed coefficients. Figure 4:21 shows the unstable positive slope of the displacement range. Figure 4:22 shows a higher speed coefficient with the hull stable in the range of yaw angle of  $+2^\circ$  with neutral stability outside this range. Figure 4:23 illustrates the pre-hump directional instability called "hooking". Within the range of  $+3^\circ$  of yaw angle the hull is unstable but outside this range it is stable. On all three figures the maximum rudder moment available is plotted. During the course of testing the trim angle and heave coefficient are also plotted. It is to be noted that directional instability is divergent and differs from longitudinal instability in that it is not oscillatory in nature.

Unfortunately, full scale directional stability tests cannot be conducted in the same manner as in the case of model tests. The correlation that was possible between model and full-scale in longitudinal stability does not exist in directional stability.

This is principally due to the inability to measure a constant yaw angle in full scale rectilinear motion. The stability of seaplane hulls depends on forebody and afterbody flow patterns. The transition of flow conditions is one which begins in the displacement range with natural instability, is modified by changes of trim as speed increases and finally becomes dependent on the shape of the wake which is changing rapidly with speed as the hull goes from displacement to planing. Conditions producing instability are further aggravated by details of water flow at the stern, particularly by the suction generated at any convex surface.

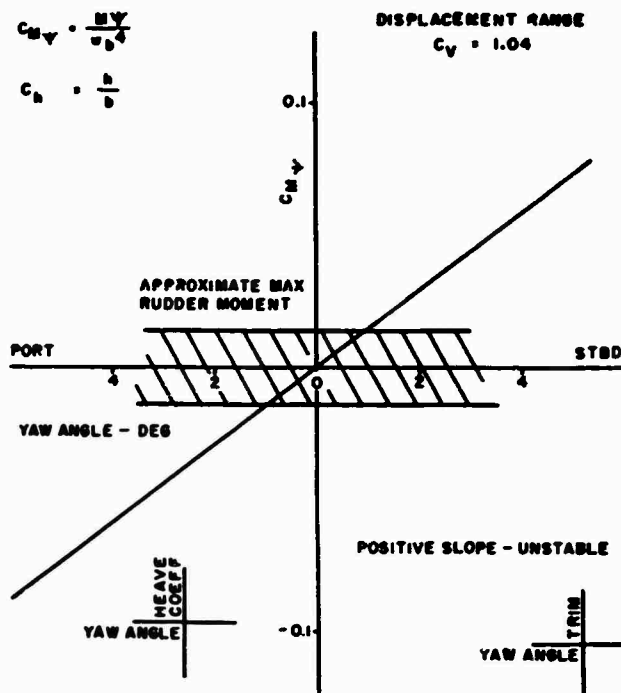


Figure 4:21

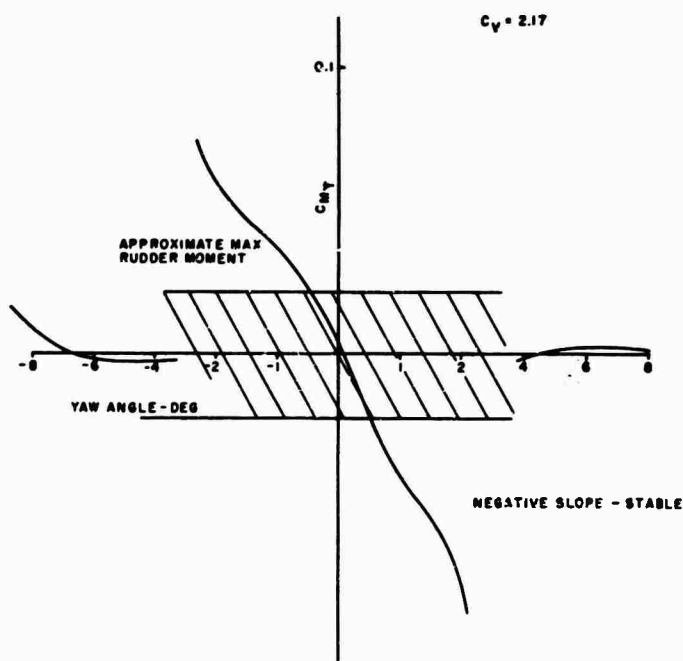


Figure 4:22

Full scale operations with a hull possessing the directional stability characteristics shown in figures 4:18, 4:19 and 4:20 have indicated that directional stability can be acceptable and that successful take-offs can be made provided asymmetric power and auxiliary devices such as hydroflaps are used.

Results from previous tests have indicated that prehump directional stability is not seriously affected by wind strength,

and therefore, data obtained during tests under other than calm conditions can be utilized. However, the angle between

the wind and the take-off course is critical. In developing test techniques, the British have determined that elevator settings have negligible effect on directional stability. They have also determined that roll angle has negligible effect on directional stability. However, in full scale tests it is considered that a combination of high trim angle and weak lateral control results in hull roll angles that contribute to directional stability difficulties.

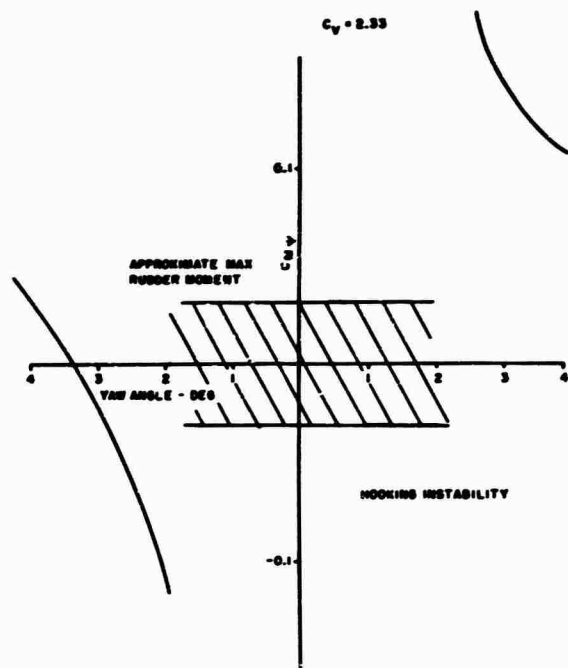


Figure 4:23

At speeds past the hump, rudder control becomes effective and direc-

tional stability is less of a problem and is usually, for most seaplanes, controllable with rudder alone. In recent developments, high speed directional instability at low trim angle has been encountered. This phenomena appears to border on being oscillatory and occurs when the hull is essentially planing on the forebody alone. However, it does not appear to be limited to the forebody alone. Neither does it appear to be limited by forebody bottom shape since the phenomena has been observed on V-shape as well as rounded forebody hulls.

#### 4.7.2 TEST PROCEDURE

There are several tests that may be conducted to graphically represent the directional stability of a seaplane. Even more so than in the case of longitudinal stability, there is no directional stability condition which defines the limit of acceptable directional stability although Military Specification MIL-D-8708 has attempted to define the limit of course deviation during take-off. Therefore, the testing procedure is basically qualitative and tries to determine the ability of the seaplane to make take-offs without unnecessary course deviation.

A statistical study is possible wherein take-off runs are made under several conditions and the degrees of deviation from intended course are recorded. Tests might be conducted under the following conditions:

- a. Elevator, aileron and rudder neutral.
- b. Elevator and rudder neutral, full right aileron.
- c. Elevator neutral, full right rudder and aileron.

Such tests require an oscillograph recording of a directional gyro to accurately determine the degrees deviation from course occurring during a pre-determined number of seconds (15 for example). If an oscillograph is not available, the co-pilot may record the following information on the data card:

- a. Starting heading.
- b. Ending heading (after 15 sec).
- c. Power.
- d. Wind conditions.
- e. Flap deflection.
- f. Configuration.
- g. Weight and CG position

A second statistical method is to maintain take-off heading while noting those take-offs which require the use of asymmetric power. A third statistical method would be to begin the intended take-off course into the wind and at some equal angle to both the left and right of the wind. The direction in which the instability is manifested is then noted as well as the number of unstable runs.



The final method, which is quantitative in nature, is to note the wind direction and magnitude, then make constant speed runs at standard increments of wind angle from upwind to downwind both left and right. During these tests the intended direction is maintained and the moments necessary to counteract any directional instability are noted. A moment equal and opposite to the applied moments required to maintain the intended direction is then noted as the "hooking" moment. Calibrated torquemeters are required. Oscillograph or photopanel recordings provide the only suitable method of determining the value of applied corrective moments. The following quantities should be recorded continuously during each run:

- a. Run No.
- b. Right and left engine
  - (1) RPM
  - (2) MAP
  - (3) Torque
- c. Directional gyro
- d. Control surface position
  - (1) Aileron
  - (2) Elevator
  - (3) Rudder
- e. Airspeed
- f. Waterspeed
- g. Hull trim angle

The investigation may be conducted at the speeds prevalent in the pre-hump range. Each run should be stabilized on the intended heading and at the desired waterspeed. The waterspeed is held constant for various headings. The waterspeed is then changed and the headings repeated. Accelerated runs to take-off may also be made and the variation of hooking moment with waterspeed determined for various wind angles.

### 4.7.3 PRESENTATION OF RESULTS

Statistical data for accelerated runs are presented as a bar graph in figure 4:24 (a) and (b), where (a) presents the percentage of total runs made that were unstable and (b) presents an extension of (a) which not only gives the hooking direction of all unstable runs but also shows data for hooking direction for runs made at a wind angle of 30° left and right.

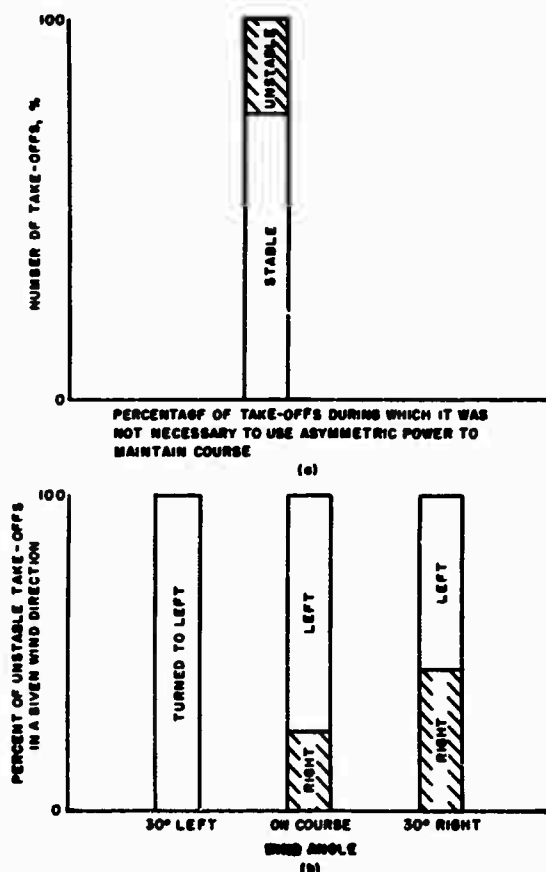


Figure 4:24

Figure 4:25 is a polar plot, the construction of which requires an estimation of the applied corrective moments. From the torque and RPM data obtained from the instrumentation, thrust for each engine may be computed and, knowing the engine arm, the moment determined. Curves of rudder lift (side force) must be available to determine the side force due to rudder deflection. In order that the forces producing the hooking moment act only on the hull, the wings should be level to eliminate wing float reaction. The hooking moment, as determined from applied corrective

moments to maintain intended heading, includes aerodynamic as well as hydrodynamic forces.

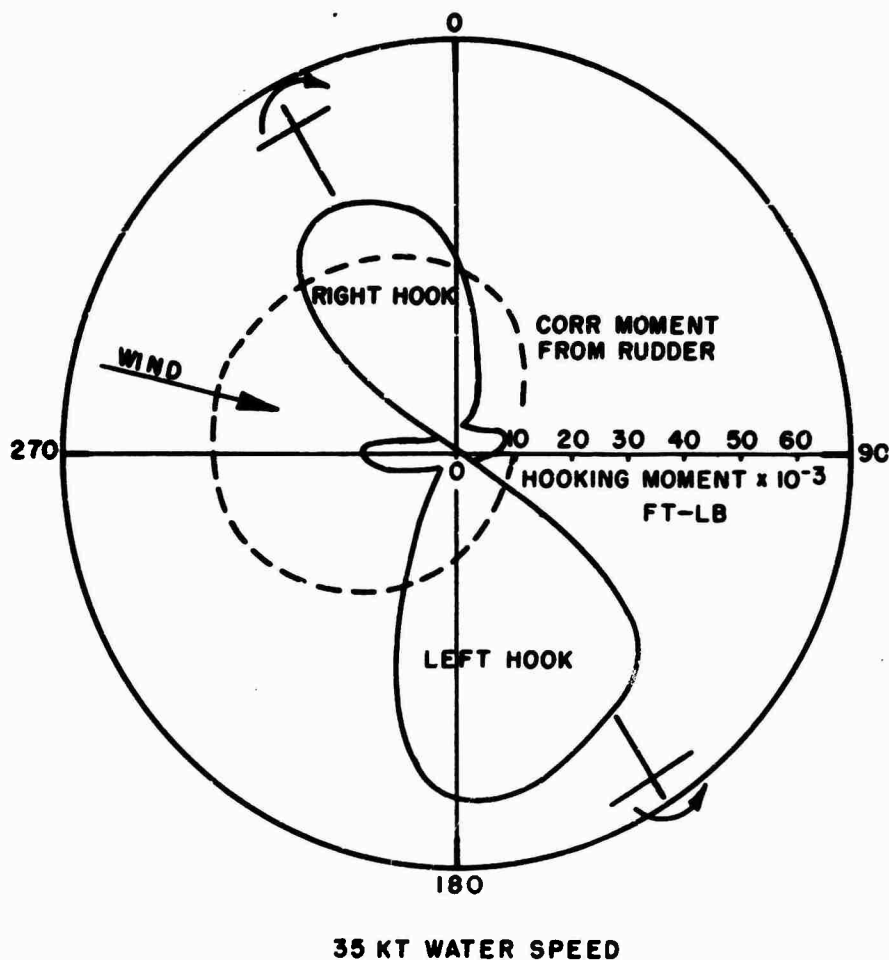


Figure 4:25

Figure 4:25 also includes the maximum amount of corrective rudder moment that may be applied during runs in any direction at a waterspeed of 35 kt. The excess hooking moment over the available rudder moment can be compensated for by the use of asymmetric power or auxiliary devices such as hydro-flaps. A separate plot similar to figure 4:25 for each of several waterspeeds is usually determined.

#### 4.7.4 CONTROL

Directional control during taxiing or take-off involves control about all three axes and not just the vertical axis. As a general rule, directional control at pre-hump speeds is weak and sometimes inadequate thereby requiring the use of asymmetric power to maintain an intended course. At speeds past hump, directional control is usually adequate to maintain heading. The evaluation of directional control cannot be treated separately as in the towing tank because the directional control is related to both lateral and longitudinal control. Because of the presence of many variables the quantitative data presented in figure 4:25 does not present the entire picture and even the inclusion of force and position instrumentation is not sufficient to adequately determine the adequacy of control. Therefore the prime evaluation is based on pilot reaction and judgements. Usually as the pilot maneuvers the seaplane, he is constantly displacing and varying the control surfaces. He is, therefore, interested in low speed control harmony. He is also interested in the wind and wave conditions wherein the limit of control surface application is insufficient to maintain an intended attitude on the water. Qualitatively the pilot evaluates seaplane directional control by providing answers to the following questions:

- a. What is the maximum wind angle wherein directional control can be maintained with the use of rudder alone during take-off?
- b. Under the conditions must the application of directional control be accompanied by the application of lateral control?
- c. How effective are the controls and to what degree are displacement and force related?
- d. What sea state limits the effectiveness of directional control?
- e. What is the technique that requires the least application of directional control during take-off?

#### 4.8 LATERAL STABILITY AND CONTROL

It has already been stated that the ability to maneuver a seaplane on the water and the ease of take-off on a pre-determined course involves longitudinal, directional and lateral stability and control. The situation is analogous to the problem of directional stability and control. That is, the problem of lateral stability cannot be isolated and consequently cannot be evaluated by a specific test.

During low speed maneuverability tests, the pilot should be required to qualitatively determine the effectiveness of lateral control. During longitudinal stability landing and take-off runs, the lateral characteristics should be investigated especially in the pre-hump region. The optimum take-off and landing techniques, with regard to total control deflection, must be determined in a qualitative as well as a quantitative sense. The information obtained may then be used to determine the envelope of permissible operations in regard to wind strength, gross weight and CG position.

From the results of previous full scale testing it is known that in the region of hump speed the seaplane hull assumes a large trim angle. Because of limited lateral control, it may be more suitable to keep the hull at lower trim angles in the pre-hump region thereby providing better lateral and directional control.

## 4.9 TAKE-OFF PERFORMANCE

### 4.9.1 DISCUSSION

The take-off performance of a seaplane is expressed as a measure of the time and distance required to become airborne. Based on considerations of controllability and instability, the best take-off performance is usually a compromise of best elevator deflection. Acceleration required for good take-off will vary with elevator deflection. Low elevator deflections at hump speed may cause low limit porpoising while intermediate deflections near take-off may lead to upper limit porpoising. It is therefore almost certain that optimum take-off is accomplished by manipulation of elevator rather than with a constant elevator setting throughout the run.

Realizing that pull speed, flap position, elevator angle, gross weight and wind condition will affect the take-off time, it is interesting to consult figure 4:26. Figure 4:26 originally presented in reference (12), is a compilation of take-off data pertaining to various types of seaplanes under all conditions of gross weight and take-off procedure. The interesting feature of the figure is that despite all the known variables affecting take-off time and distance, a logarithmic plot of take-off distance versus get-away speed times take-off is fairly well represented by a single line for many different seaplanes. Within an accuracy of  $\pm 5\%$ , all take-offs can be represented by the following formula:

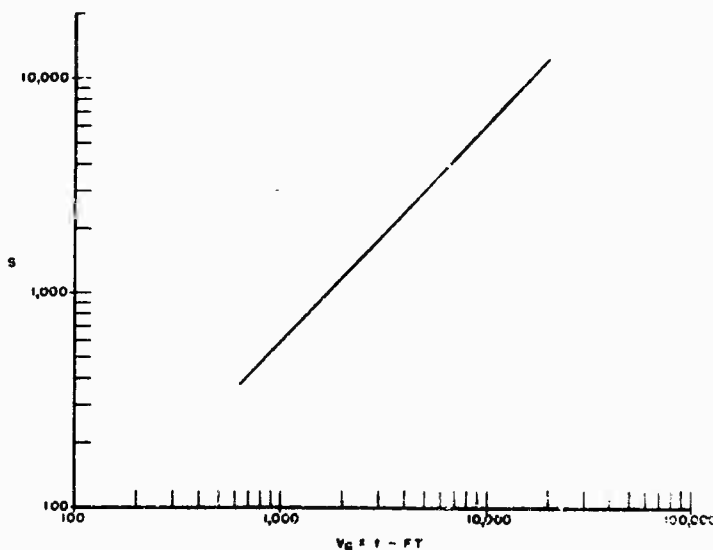


Figure 4:26

$$S = 0.60 V_g t \quad (4-5)$$

where  $S$  is the distance traveled in feet,  $V_g$  is the get-away waterspeed in ft/sec and  $t$  is the take-off time in seconds. Since it is rarely required that an operational group know the take-off distance within 5%, a spot check to within  $\pm 5\%$  using the above formula is usually adequate in full-scale test.

In previous full scale testing with only about 10 measured take-offs, the plot of points similar to figure 4:26 for one hull type seaplane has shown the formula to be as follows:

$$S = 0.65 V_G t \quad (4-6)$$

It will be remembered from basic physics that for uniformly accelerated motion, the distance traveled by a body is represented by:

$$S = 0.5 V_G t \quad (4-7)$$

where the instantaneous velocity ( $V_G$ ) is the get-away speed as in equation (4-6). Equation (4-5) is surprisingly similar to equation (4-7) the difference in the constant being probably due to full scale departure from theoretical uniformly accelerated motion. Since equation (4-6) was based on a small number of take-offs, it is felt that a larger number of take-offs (perhaps 100) would in all probability adhere to the distance as computed in equation (4-5).

#### 4.9.2 TEST PROCEDURE

Prior to conducting measured seaplane take-offs, a suitable course must be laid out. If such a course cannot be conveniently laid out, take-off distances can be estimated from longitudinal acceleration and airspeed data. Figure 4:27 illustrates a typical Seadrome take-off course marked with well-anchored buoys to facilitate measurements. Once the course has been laid out, distances and included angles can be determined by triangulation. The only requirement during testing is that the seaplane remain as close as possible to the line between buoys No. 1 and No. 2. During testing, an observer at the transit observation point (TOP) follows the path of the seaplane until the take-off is commenced. The angle C is then noted. The seaplane is tracked until take-off is observed and angle D is noted. Since all other distances and angles are known, the distance A-B can be computed. The observer at the TOP should have a stopwatch to provide the additional information of the duration of the take-off run.

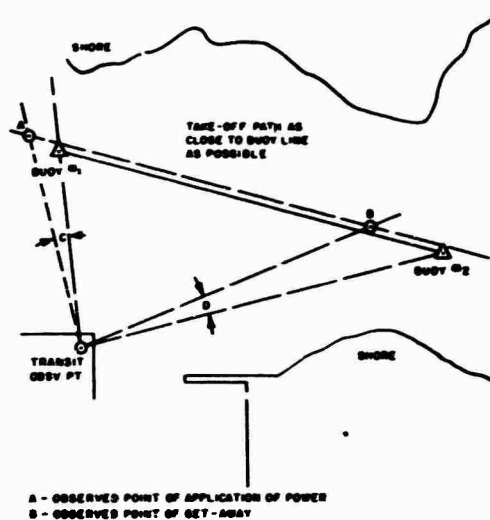


Figure 4:27

The point at which the take-off time is begun or the procedure used is one of academic interest as long as the results can be used for checking contract guarantees. Procedures have included beginning timing as engine power passes 30" MAP, and beginning timing when full engine take-off power has developed. With the advent of superior reverse thrust propellers, it was considered that it would be more realistic to begin timing when the forward water speed is zero. When water speed is zero, the stopwatch is begun and at the same instant take-off power is applied. If the seaplane should possess directional instability or longitudinal instability thereby requiring asymmetric thrust and/or changes in elevator setting, it is much more valid to compute take-off time from zero water speed. Take-off capability should include all additional time required to correct directional difficulties. Any arbitrary method of beginning take-off time should be well defined and suitable for comparison purposes.



Take-off runs should be conducted in relatively calm winds (not greater than 5 kt), and at several representative gross weights. Since CG position is important due to its effect on elevator control, the take-off performance can be limited to that CG which results in the most critical longitudinal control. Wing flaps will usually be positioned for normal take-off unless, as a result of contractor recommendation, some other procedure for flap deflection has been developed.

Various runs at several fixed elevator settings are made until the range of usable elevator has been determined for best acceleration. Once optimum elevator movement has been determined the pull speed may be varied in order to determine minimum time for take-off. Pull speed usually begins below the fly-off speed; that is, the speed at which the sea-plane will fly off the water using the elevator deflection for best acceleration.

An oscillograph or photopanel may be installed to record various quantities. Usually the results of the initial portion of the run are not required and, hence the instrumentation need not be turned on until reaching hump speed. Whether or not automatic recording is used a data card should contain the following information:

- a. RPM
- b. MAP
- c. BHP
- d.  $V_0$  at get-away
- e. Time
- f. Pull speed
- g. TO configuration
- h. Weight and CG
- i. Wind and water conditions

#### 4.9.2.1 INSTRUMENTATION

Data may be recorded by oscillograph, photopanel, magnetic tape or manually. Figure 4:1 indicates those quantities which are considered desirable to record during take-off testing. It can be stressed again that take-off time solely by the use of a stopwatch in the aircraft plus a stopwatch and transit on the beach may be sufficient to establish adherence to the curve of figure 4:26. An oscillograph or magnetic tape installation is preferred to a photopanel and, if such is installed, trim angle, longitudinal acceleration elevator position, airspeed and/or water speed should be recorded. In all cases, the extent of the tests being conducted will govern the nature and amount of instrumentation.

### 4.9.3 PRESENTATION OF RESULTS

Figure 4:28 shows the results of constant elevator accelerated runs from which may be determined the optimum elevator movement for best acceleration at a given gross weight and CG position. This type presentation requires a time history of longitudinal acceleration for constant elevator runs. Many of these constant elevator runs can be made during longitudinal stability investigations.

Once the fly-off speed for best acceleration and optimum elevator angle has been determined, figure 4:29 can be constructed on the basis of a variation of pull speeds versus take-off time or distance. The investigation may be conducted at the most critical CG position or any other required position. Figure 4:30 is constructed from the variation of gross weight and take-off time for the minimum pull speed.

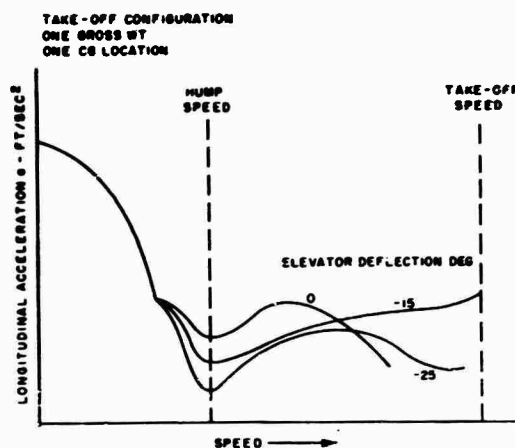


Figure 4:28

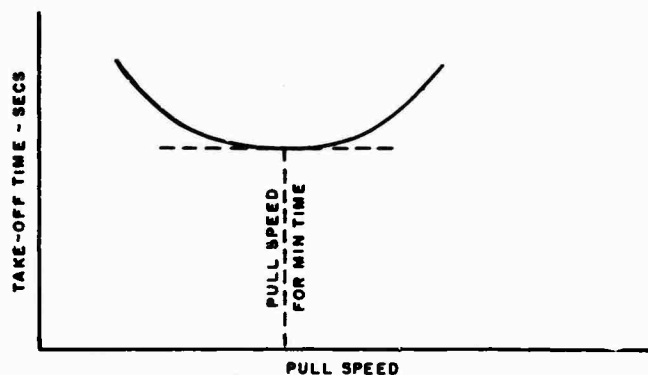


Figure 4:29

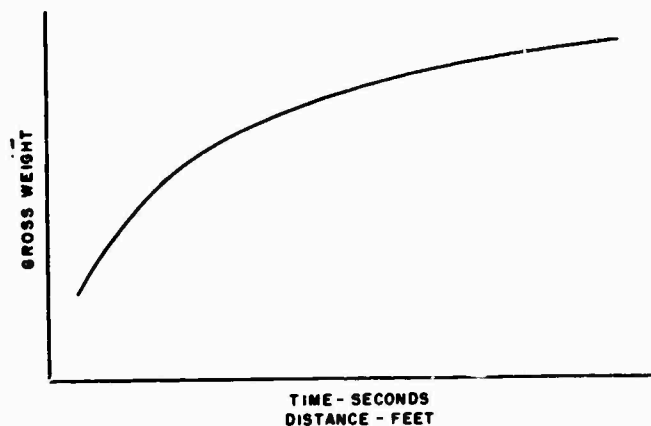


Figure 4:30

Figure 4:26 may be used for either a quick check of limited data or as a means of presenting a large amount of take-off data.

#### 4.9.4 ANALYSIS

The data of figure 4:26 is based on the results of the work presented in reference 16. Data obtained under various conditions adhere within  $\pm 5\%$  to the relation for take-off distances expressed in equation (4-5). It was specified that take-off computations should be conducted in winds of 5 kt or less. Results obtained by both British and U. S. seaplane testing facilities have specified the need for correcting to zero wind conditions, thereby not specifying the limiting wind velocity. Charts based on Diehl's formula:

$$\frac{S_w}{S} = \left( \frac{t_w}{t} \right)^2 \quad (4-8)$$

are available which specify that for a take-off speed of 80 kt, corrections up to a limiting wind velocity of 55 kt may be made. Formula (4-8) provides a suitable means for correcting results to zero wind velocity. There is, however, an additional complication in the correction of take-off data to zero wind. In recent seaplane work in the U. S., results contained in references (17) and (18) have tended to show that the resistance of a seaplane hull increases in waves. Since an increase in wind velocity is always attended by increased wave action, the distinct possibility exists that the additional wave resistance may more than negate the decreased take-off time due to the additional air mass flow brought about by increased wind. It is considered that further investigation is required in order to define the phenomena of increased resistance from wave action. In the meantime, take-offs should be conducted in wind conditions of 5 kt or less. A standard of 10 kt of wind might be used wherein take-off times less than 10 kt could be corrected up to 10 kt or take-off times in winds greater than 10 kt and up to 20 kt could be corrected down to 10 kt. Establishment of such a standard accompanied by a suitable correction procedure might have certain inherent errors, but certainly not as great as correcting take-off times from 20 kt down to zero velocity. At any rate, take-off runs in higher winds should be attempted for correlation purposes.

## 4.10 HYDRO-SKIS AND HYDRO-FOILS

### 4.10.1 GENERAL

The development of hydro-skis and hydro-foils has been generated principally to satisfy the requirement of low landing impacts thereby permitting operations in higher sea states. The terms skis and foils have, in a good many cases, been indiscriminantly applied to almost any auxiliary lifting surface. The following descriptions classify the various ski surfaces and follow the material contained in reference (19).

a. Hydro-skis. Basically the hydro-ski is the hydrodynamic equivalent of the landing wheel. The ski is generally located near the CG in order to better absorb the energy impact. There is little or no buoyant force, the lift being created by dynamic pressure on the bottom of the ski particularly when operating on the surface of the water. There are many variations in the shape of hydro-skis as well as in the configuration or arrangements between ski and body.

(1) Pantobase. This type of gear is suitable for operations from "wet" surfaces such as mud and snow as well as from hard prepared surfaces. This type usually contains a wheel recessed within each of twin skis. For operations from prepared surfaces the wheel extends below the bottom surface of the ski. For soft surfaces the wheel protrudes only slightly while for water operations the wheel is retracted into the ski bottom surface. For operations on the water the plane must possess suitable means for flotation.

(2) Hull Auxiliaries. Most full scale ski arrangements have been installed in hull type seaplanes. The surface is therefore auxiliary since the flotation provisions are already present in the hull. Both single and twin ski installations (JRF and PBM) have generally shown that the ski equipped aircraft can operate in higher sea states and absorb higher loads than those hulls not equipped with skis. The skis presently used in full scale testing have had a rather distinctive shape. It is in effect a miniature hull bottom incorporating a rounded keel, deadrise, chine flare and a distinctive chine. The ski, however, can have any shaped bottom including round, Vee or flat, commensurate with its requirements.

(3) Ditching Aids. In the event that land based aircraft are required to ditch at sea, the hazards and expected extensive structural damage of open sea landings can be alleviated by the use of a small retractable ski. Since the ski would be used only once, the ski and the mechanism used to lower it could be of the simplest design thereby holding the weight penalty of the ski installation to a minimum. The use of such a ski might conceivably allow the ditched aircraft to stay afloat longer as a result of incurring less damage on contact.

(4) Land-Water. Several small airplanes have been operated successfully off and on beaches and ramps by using snow skis. This type ski has a flat bottom with bow slightly curved upward. Since there is no buoyancy either in the ski or in the vehicle to which it is attached the ski must be going fast enough to support the vehicle by dynamic lift. The launching procedure is to build up speed either on the beach or on the ramp. When sufficient speed is attained the plane enters the water where speed is further increased until take-off occurs. Wheels may also be incorporated. The entire installation of wheels and skis will weigh less than the same installation for the true water-based version.

Almost all of the above applications for the use of hydro-skis have been confined to the modification of existing types. The development of the F2Y represented the first attempt to design a water based vehicle incorporating both jet engines and twin skis. The F2Y, however, had many faults including high lateral accelerations.

b. Hydro-foils. Like the hydro-ski, there are many types and arrangements of the hydro-foil. The foil is designed to operate beneath the surface of the water and produce lift in a manner similar to airfoils. Although hydro-foils have been subjected to a variety of model tests, full scale application has been limited to surface craft where they have been eminently successful. Several hydro-foil boats have shown that speeds up to 40 kt are possible in 3 ft seas. When in motion, the hull of the boat rides above the surface of water supported by the hydro-foils in either a three or four point suspension pattern.

Hydro-foils, unfortunately like ships propellers are subject to the effects of cavitation which is a phenomena that occurs when the vapor pressure of the fluid at some

point on the ski equals the total pressure at the same point. The speed at which this phenomena occurs makes the use of hydro-foils for high speed seaplane applications questionable and further investigation is required. Suffice to say that with the onset of cavitation, lift is reduced. Lift is also reduced as the hydro-foil gets closer to the surface of the water. Hydro-foils have been tried in many types of installations including the ladder foil where several foils are located directly beneath and above each other. Surface piercing struts set at an angle have also been used to produce underwater lift. Dihedral, sweepback and other ski-forms have been tested.

Apart from individual tests on hydro-skis and hydro-foils, several tests have been made using a combination ski and foil and referenced in at least one instance, as a hydro-foil ski.

#### 4.10.2 TESTING AND APPLICATIONS

The major portion of the work in the field of skis and foils has been done in the towing tank. Studies have been conducted on many phases including:

- a. Interference effects between body and ski.
- b. Optimum ski or foil configuration (planform, etc.)
- c. Unporting and submergence characteristics.
- d. Resistance and planing characteristics.
- e. Impact and rough water characteristics.
- f. Attachment and operating characteristics.

A good deal of information has been tabulated but the number of full scale applications has been disappointingly small. The following is a partial list of some of the installations that have been tested under full scale conditions:

- a. JRF single and twin ski.
- b. PBM single ski.
- c. OE universal twin skis.
- d. SNJ twin skis (with and without flotation gas).
- e. F2Y twin and single ski.
- f. C-123 pantobase twin ski.
- g. P2V snow and mud tri-ski.

All of the above vehicles enjoyed a certain measure of success, however, they were modifications of existing types while the F2Y represents a test vehicle actually designed as a ski-equipped high performance seaplane.

The problems of the F2Y were numerous, but they did illustrate that the concept was feasible. The single ski installed on the F2Y proved to be much larger than was needed while the shock absorber installation required additional development work. Unporting was never a problem since the ski was so long that it emerged almost as soon as power was applied. During take-off, more and more of



the ski came out of the water until eventually at high speed just prior to take-off only about 1/10 of the ski was being acted on by dynamic pressure. Full scale take-off tests at constant elevator settings showed that large up elevator settings were required during the initial portion of the run but that these angles should be reduced by the pilot during the later portion of the run.

Reference (20) records some observations made at NATC during testing of aircraft equipped with skis. Generally, these full scale tests have illustrated that, although impact is considerably less than similar aircraft without skis, there are several undesirable characteristics. One of these is the adverse spray during unporting. Another is the high trim angles the hull assumes during unporting and submergence. These high trim angles introduce lateral and directional control problems. The test vehicles used to demonstrate ski capabilities have for the most part been underpowered. As a consequence, warm humid days with calm winds have been particularly difficult in that there is insufficient excess thrust to overcome hump resistance during unporting.

A full hydrodynamic characteristics program has never been conducted at NATC on a ski equipped seaplane (Jan 1958) except as noted above. It is felt that the test procedures contained in this manual for testing conventional seaplanes can be applied with little modification to the ski or hydrofoil seaplane. The following comments are made relative to several standard tests as they might affect a ski-equipped seaplane:

a. Water maneuverability, can be measured in the same manner as for hull type seaplanes. A protruding ski arrangement can be expected to increase resistance but at the same time possibly reduce turning diameters.

b. The spray pattern differs in that it does not gradually fall aft in a readily distinguishable pattern as in the case of a hull type seaplane. The spray is usually short in duration but high in intensity and occasioned by the ski unporting at high trim angles. After the ski has unported, spray is usually sufficiently aft to be of much less concern except for the tail section. The spray thrown up during unporting will probably be of such intensity that the technique of photographing against the seaplane hull will be difficult if not impossible especially if the seaplane has a low hull depth.

c. Longitudinal stability and control can be investigated by those methods already specified with little or no changes. Control problems may be such that the determination of unstable areas from constant elevator runs becomes difficult.

d. Lateral and directional stability and control problems will probably be centered mainly on the unporting region where high trim angles and low speeds make controllability difficult.

e. The take-off performance will be, as usual a function of the resistance. However, the resistance versus speed curve for the ski-equipped seaplane has the same general shape as the resistance curve for hull type seaplanes. Take-off technique will require the development of optimum pilot technique based on a qualitative investigation.

f. Rough water tests including seaworthiness evaluation will depend on the anticipated characteristics of the full scale article.

## **4.11 ROUGH WATER AND SEA WORTHINESS**

### **4.11.1 GENERAL**

The subject of rough water capabilities of seaplanes has always been of special interest to seaplane proponents. The fact that seaplane operations need not necessarily be restricted to wave heights of 3 ft or less would result in a tremendous increase in the scope of operations. The requirement for operations in at least 8 ft seas has been frequently set by considerations of anti-submarine warfare. The ability to land in the open sea under a variety of conditions would greatly increase the seaplanes capabilities in operations against submarines. Therefore much consideration has been given to an analysis of the loads sustained by a seaplane when operating in waves of varying magnitude.

A review of the above problem indicates that there are two prime factors that govern the ability of a seaplane to operate in any given sea condition. These factors are strength and controllability. The strength factor is tested as thoroughly as possible in towing tanks but so little is actually known of impact that full scale results are required to supply much needed information. The controllability factor is generally investigated full scale in a qualitative sense, and is conducted as specified in sections 4.2, 4.6, 4.7, and 4.8.

#### 4.11.2 THEORY OF IMPACT

Theoretical and experimental studies on landing have been conducted with three basic objectives in mind:

- a. The determination of the total force of the water reaction and its variation with time and submergence.
- b. The intensity of the water pressure on the bottom plating and its distribution.
- c. The effect of elasticity in the structure connecting the planing bottom with the masses of the seaplane.

Each of these objectives has been investigated, both separately and concurrently during many different programs. A compilation of the results of these investigations by the NACA is contained by subject matter in references (21) and (22). (These references also contain many other model and full scale results on hydrodynamic phenomena). The present section is concerned with the background material associated with the efforts of investigators to establish a mathematical relationship between the impact force, the basic parameters of glide path, trim angle and velocity, and the mass of the seaplane. Section 4.11.3 and 4.11.5 deal respectively with the problems of water pressure distribution and hull elasticity.

Basic research on flat plates and straight prismatic Vee surfaces have resulted in a wealth of material concerning the landing of seaplanes. Equations for the impact force have been idealized and corrected for non-idealized conditions, thereby establishing a basic mathematical theory. The full scale seaplane hull is neither a flat plate nor a prismatic Vee, and adjustments to theory are required to account for deadrise, curvature, and other hull parameters. The adjustments have been necessary in order to develop equations which will predict loads that will be in agreement with the loads and pressures obtained from full scale results.

In determining the basic parameters defining the impact force, the ideal seaplane landing is considered. There is a flareout from the glide where the velocity becomes tangential to the water surface, and the surface is therefore penetrated without any shock. In actual conditions, the flareout does not result in a tangential velocity and the flight path is, at the moment of contact, inclined at some

angle  $\gamma_0$ . In smooth water the assumption is made that the basic parameters for impact can be represented by the following:

$\gamma_0$  - glide path

$V_0$  - velocity along the glide path

$\gamma$  - contact trim angle (assumed constant).

In order to physically define the parameters, the basic theory, as proposed by Von Karman in reference 23 is to consider a wedge penetrating the surface of the water as shown in figure 4:31 with zero trim angle. As the wedge penetrates, a unit thick slice of wedge is considered and the

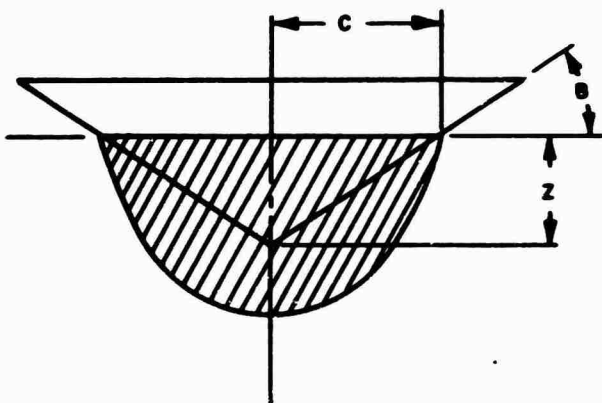


Figure 4:31

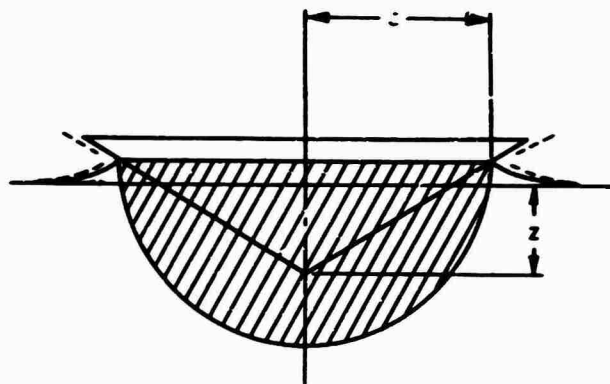


Figure 4:32

analysis can therefore be limited to two-dimensions. The total momentum is the mass of the wedge times its instantaneous vertical velocity plus an additional or "virtual mass" times the instantaneous vertical velocity. The shape of the virtual mass is shown as the cross-hatched area in figure 4:32 and increases as the wedge penetrates further into the fluid. The following quantities may then be mathematically determined:

$$(\text{vertical velocity}) \quad \dot{z} = \frac{\dot{z}_0}{(1 + m/M)} \quad (4-9)$$

$$(\text{vertical acceleration}) \quad \ddot{z} = \frac{-2 \frac{m}{M} \dot{z}_0^2}{z (1 + m/M)^3} \quad (4-10)$$

Where  $\dot{y}$  is the distance from the bottom of the wedge to fluid surface taken perpendicularly and  $\dot{y}$  is the velocity or change of vertical distance with respect to time. This represented the basic solution from which subsequent investigations were developed. Improvements were sought which would take into consideration all conceivable variables thereby producing equations which would have unlimited application. The solution proposed by Von Karman is referred to as the "expanding plate" since the wedge, as it penetrates the fluid, has a wetted width which is expanding at the same rate as a flat plate of width equal to the instantaneous width of the wedge.

The case of two-dimensional impact is hardly of more than academic interest. It does, however, illustrate the fundamental approach for three dimensional or oblique impact. In essence, the three dimensional approach to impact considers the fluid beneath the hull to be subdivided into slices of length by planes drawn normal to the keel of the float as shown in figure 4:33. As the float moves through these

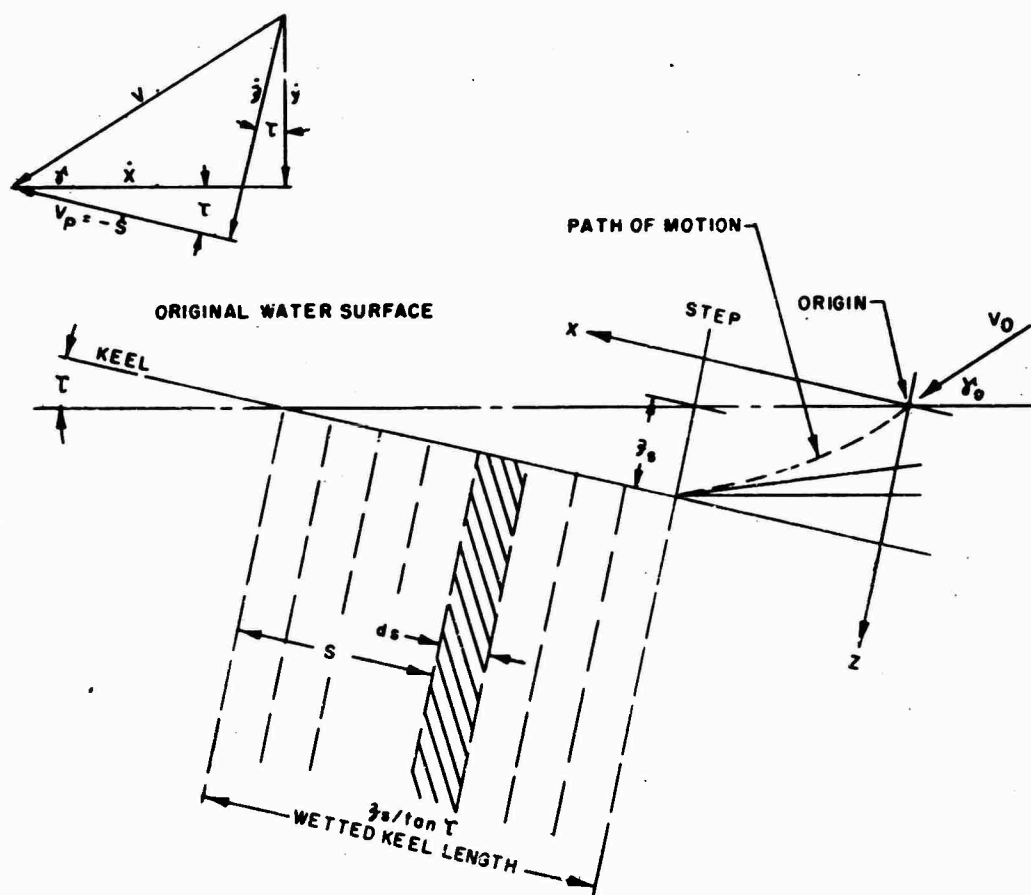


Figure 4:33

slices, the flow in each slice is assumed to be two-dimensional and identical with the flow produced by a wedge dripped vertically into the water. It is assumed that the fluid in each slice is independent of the motions in adjacent slices and that the total reaction on the hull is due to the combined action of all the slices which have a total thickness equal to the wetted keel length.

It is also assumed that only the velocity component normal to the keel governs the force contributed by each flow plane. The component of velocity parallel to the keel, however, is essential in determining the total force on the keel since it governs the degree of immersion of the keel.

The same basic procedure as applied for two dimensional impact is applied in the case of three dimensional impact with two important additions. One of these is due to the work of Wagner who first discussed the water rise on a planing section and referred to it as the "spray root". The phenomenon was briefly mentioned in section 2.3. In figure 4:32 the water rise increases the virtual mass due to the larger diameter of the cylinder beneath the wedge. The virtual mass of any Vee-shaped cross section can be defined as:

$$M_w = [f(\beta)]^2 \frac{e\pi}{2} z^2 \quad (4-11)$$

where the quantity  $f(\beta)$  represents the radius of the equivalent semi-cylinder of water associated with the immersed shape and indicates that it is some function of the deadrise.

The second correction is necessary because the planing bottom is not of infinite length but ends in a discontinuity which is the step. The correction is a function of the length-beam ratio of the wetted area and can be expressed as:

$$g(A) = 1 - \frac{\text{TAN } \gamma}{2 \text{ TAN } \beta} \quad (4-12)$$

The expression for the force acting on the bottom of each fluid slice is determined and the expression is then integrated over the wetted length. The total force acting on the hull becomes:

$$F = [f(\beta)]^2 g(A) \frac{e\pi}{\text{TAN } \gamma} \left[ \frac{z_s^3 \ddot{\theta}}{3} + \dot{z}_s^2 z^2 \right] \quad (4-13)$$

The force is therefore expressed in terms of the instantaneous acceleration, the instantaneous velocity, the trim angle and the step depth ( $\gamma_s$ ).

With the solution in the above form, the axis of reference is shifted to coincide with the undisturbed surface of the water which will be commensurate with the use of several dimensionless coefficients based on the previous approach parameters. Charts are then prepared which are based on a numerical solution. The charts are used to solve for load, velocities and draft in terms of the "approach parameter" defined as:

$$\frac{\sin \gamma}{\sin \gamma_0} \cos (\gamma + \gamma_0) \quad (4-14)$$

Reference (24) contains the development of these charts and a complete discussion of their use.

Before continuing the development of impact theory, another important concept is considered. In figure 4:34 a wedge penetrating a fluid is shown just after the start of

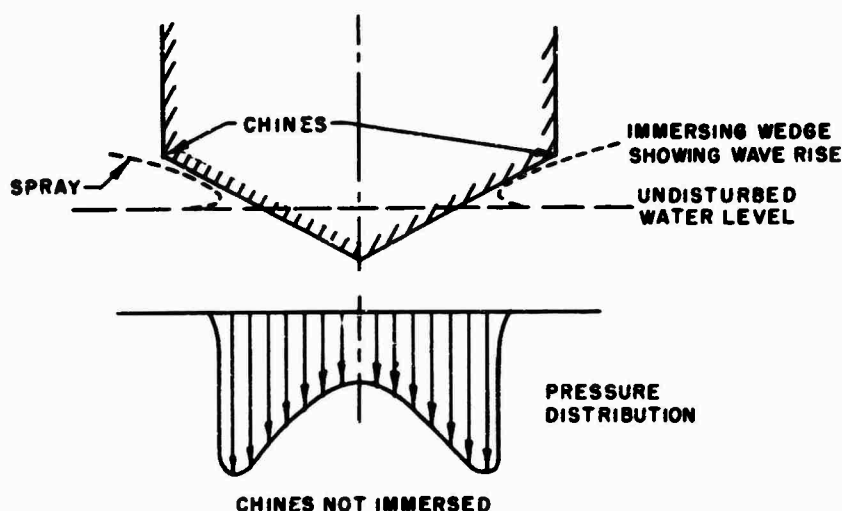


Figure 4:34

penetration while in figure 4:35 the wedge is shown just after penetration. The former case is referred to as the "chines not-immersed" or "chines dry" while the latter is the "chines-immersed" case. The discussion of impact load determination thus far presented has been concerned with the "chines dry" case. This is essentially the same as saying that the wedge has an infinite beam width. There is a counterpart to this in airfoil theory where certain corrections to the total wing lift are made for the aspect ratio.



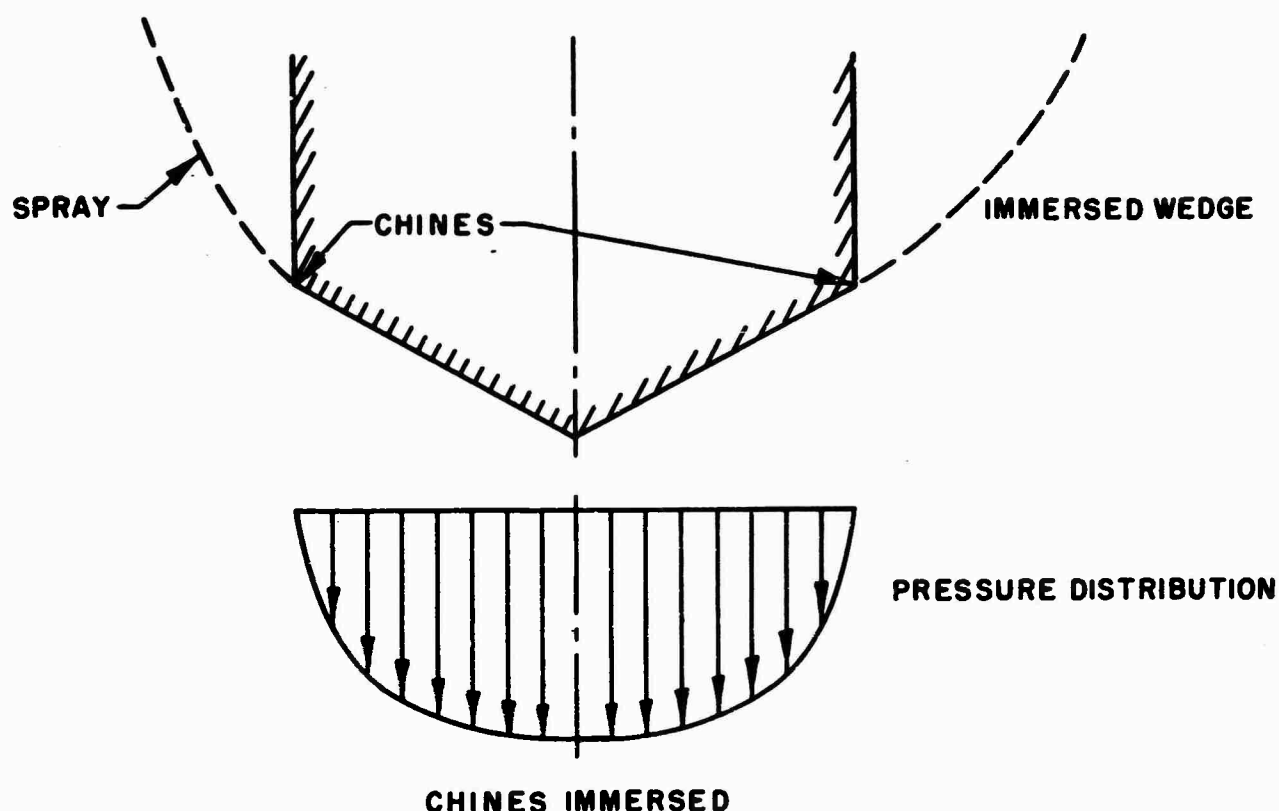


Figure 4:35

There is therefore, a point on an immersing wedge where the wedge ahead of the point has dry chines and the wedge behind the points has wet chines. As the wedge continues its penetration the point shifts aft for the case of a drop at a finite trim angle and at full immersion the chines become totally immersed and the entire wetted width is finite. In the case of a drop at zero trim, the time history of increase in wetted length will be the same along the entire length of the hull. The computation of the force on the hull depends on whether or not the chines are considered wet or dry. This is readily apparent from the pressure distribution for each shown in figures 4:34 and 4:35. Since the analysis has envisioned the flow as a summation of vertical fluid slices, differences in the flow of each unit slice can conveniently be compensated for in the determination of the virtual mass term. Therefore the resulting equation can be made to apply to the required conditions by merely adjusting the virtual mass term. Reference (25) proposed equations which were simplified analytically using this technique and solved numerically to predict impact loads for heavily loaded, narrow-beamed hulls which relate to the case of "chines immersed". The solution is based on an estimate of the deflected mass for chines prior to immersion, at the point of immersion and after immersion. The solution is in the form of charts which

are similar in form to the charts of reference (24) and are based on the same approach parameter.

In the impact theory thus far, consideration is given to the development of a force equation that will permit the construction of a time history of a seaplane impact. The carry-over of the two-dimensional case into a three dimensional case by summing up individual fluid slices depends on a determination of the deflected mass. Various corrections are added to correlate theory with experiment.

It has been suggested in previous theory that planing data could be analyzed to determine the coefficients used in defining the apparent additional mass for different cross sections of hulls. Reference (26) approached the problem by taking the equation (4-13) for the total force and presenting it in a slightly different form. For the case of steady planing the first term in the bracket of equation (4-13) is zero. By changing the notation of the equation to terms of draft in the Y-axis (i.e. perpendicular to the undisturbed water surface) the following equation is derived for a planing hull with chines above water:

$$F = \frac{\pi}{2} \underbrace{(1.19y)^2 \cot^2 \beta}_{A} \underbrace{\left(1 - \frac{\tan \gamma}{2 \tan \beta}\right)}_{B} v^2 \underbrace{\sin \gamma}_{C} \underbrace{\left[ C_g + \frac{e g y^3}{3 \sin \gamma \tan \beta} \right]}_{D} \quad (4-15)$$

where the expression A is a modified Wagner function accounting for wave rise; expression B accounts for a down wash correction at the step; expression C is an experimentally determined correction for the Froude number for low speed planing;  $C_g$ , a correction due to the effect of gravity on inertia forces, (approaches the value of 1 for high speed planing); expression D is a compensation for the effects of buoyancy which are more marked at low planing speeds. The correction is required because the original assumption that identical flow exists in each of the fluid slices is not valid. At lower speeds the value of  $C_g$  will be less than unity thereby reducing the total force by reducing the deflected mass. The final step in reference (26) develops the force due to chines being immersed. The form is as follows:

$$F = \frac{\pi}{2} (1.92 Z \cos \gamma)^2 \cot^2 \beta \left[ 1 - \frac{Z \sin \gamma (y-z/2)}{y^2 \tan \beta} \right] \\ + v^2 \sin \gamma C_g + \underbrace{C_s \frac{e z}{\tan \beta} v^2 (y - Z \cos \gamma) \sin \gamma \cos \gamma}_{E} \\ + \frac{e g z}{\sin \gamma \tan \beta} (y^2 - Zy + \frac{z^2}{2}) \quad (4-16)$$

This case differs from the chines not immersed by the addition of the expression E which accounts for the steady-flow force acting on the submerged keel behind the chine intersection. Both of these expressions agree reasonably well with test results. However, reference (25) states that equation (4-16) is insufficient for heavily loaded narrow-beam prismatic surfaces. The left hand side of equation (4-16) can be measured in the towing tank. The quantities of the right hand side are also known and therefore the coefficients and correction factors may be determined or verified. The method illustrates clearly that steady planing is a special case of impact phenomena. It is equally clear that the equation has certain limitations and can not be widely applied for all trims, loads and speeds.

One further modification of impact theory is contained in reference (27). This work considers the effect of changes in trim during impact and presents the equations of motion for variable trim. It shows that if the trim is constant, the solution yields the same results as previous work which considered the trim as being fixed during impact.

Each attempt to provide workable formulae for the effects of impact within the entire operating range of seaplanes usually ends in a compromise. One investigator considered that because the center of impact is not below the CG, the inclusion of an eccentricity factor expressed in terms of the radius of gyration and the distance between the center of pressure and the CG is required. At best each formula developed will probably contain some numerical constant which is usually determined empirically. The development of satisfactory formulae for impact analysis is complicated and any solution is usually based on some or all of the following simplifying assumptions:

- a. The water surface is smooth
- b. The seaplane is a rigid body
- c. The trim angle remain constant during the impact
- d. The wedge bottom of the hull is not flared
- e. The finite width of the hull has no effect on the motion
- f. The wing lift equals the weight of the seaplane
- g. Buoyancy and viscosity forces may be neglected.

#### 4.11.3 PRESSURE DISTRIBUTION

The impact theory presented in the previous section discussed the difficulty of obtaining an equation for the hydrodynamic force based on virtual mass. The theoretical description of the rise of the water surface in contact with a body immersed in a fluid is difficult. The interdependence between the rise of fluid, the virtual mass and the resulting force on the body was practically unanimously agreed to be influenced primarily by shape as evidenced by the deadrise angle. Although this approach leads to valuable rationalization of seaplane design, it is felt that the way in which the force of an impacting body is distributed on the hull bottom rather than the force itself, is essential to understanding the details of load distribution required for proper design.

To investigate the question of pressure distribution, it is first necessary to determine accurately the details of the fluid flow pattern in the vicinity of the body. The concept of potential flow of an ideal fluid is used to investigate the flow formation on a flat lamina expanding in width at a constant rate. It is possible to determine the pressures on an immersing wedge by considering the wedge to have an intersecting width increasing at the same rate as the expanding lamina.

Reference (28) is one of several references which reports an investigation of the problem of flow about an immersing wedge. The development of the pressure distribution on an expanding lamina as presented in reference (28) duplicates the work of Wagner, but with different emphasis. If the pressure on the flow field is written by considering a steady penetration of the wedge the result is as follows:

$$P = \frac{\rho v^2}{\lambda} \left[ \frac{1}{1 - \frac{x^2}{c^2}} - \frac{\lambda/2}{\frac{c^2}{x^2} - 1} + \frac{\lambda}{2} \right] \quad (4-17)$$

where  $\lambda$  is the wetted length ratio  $\ell/b$ ,  $C$  is the variable wetted width (a function of immersion) and  $X$  is the point in question. The first term is the effect of expansion of wetted width. The second term is the reduction due to the velocity along the lamina and the third term adds the stagnation pressure of the fluid at infinity. From equation (4-17) the following values are obtained:

$$P_{\max} = \frac{\rho v^2}{2\lambda^2} (1 + 2\lambda^2) \quad (4-18)$$

$$P_k = \frac{\rho v^2}{2} (2/\lambda + 1) \quad (4-19)$$

where  $P_k$  is the pressure at the center of the lamina.

The mathematical treatment indicated that an infinite velocity is required at the edge of the lamina and therefore can not be satisfied. The investigation was concentrated at the edge of the lamina in the region that Wagner termed the "spray root". The flow field in the "spray root" and shown in figure 4:36 is based on the use of the complex variable. The analysis is defined only for the case in which the X-axis in figure 4:36, extends to infinity in both directions (i.e., chine not immersed). This immediately recalls to mind the corrections necessary for impact cases wherein the wetted width is not infinite.

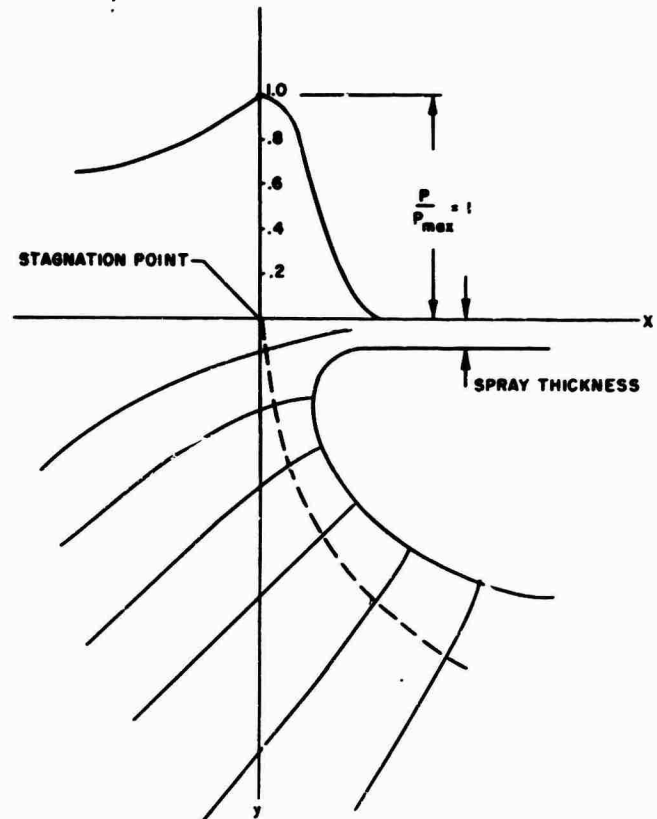


Figure 4:36

A comparison may be made of the maximum pressure in the spray root region by assuming that this maximum pressure occurs at the same point as predicted by the expanding lamina. By defining:

$$\lambda = \frac{Z \tan \beta}{\pi} \quad (4-20)$$

and substituting into the expression for maximum pressure in equation (4-18) the following comparisons are made:

$$\text{Spray root } P_{\max} = \frac{\rho V^2 \pi^2}{8 \sin^2 \beta} \left( 1 - \frac{4 \tan^2 \beta}{\pi^2} \right) \quad (4-21)$$

$$\text{Expanding lamina } P_{\max} = \frac{\rho V^2 \pi}{8 \sin^2 \beta} \left[ 1 - \left( 1 - \frac{8}{\pi^2} \right) \sin^2 \beta \right] \quad (4-22)$$

These two equations are practically identical for small deadrise angles where the term in the bracket approaches unity.



The similarity between steady planing and impact has been suggested several times in the discussion of impact theory. In full scale tests it is easier to measure pressures on a steady planing wedge than on an impacting wedge. In the case of the impacting wedge, pressure recording is difficult. This is due in part to the rapidity with which pressure variations transverse the wedge bottom as the wedge penetrates deeper into the fluid. Several tests were conducted at a fixed trim and variable speeds which showed that the pressure distribution was in fact similar to that shown in figure 4:34 for the case of chines not immersed.

Reference (29) continues the pressure concept and investigates the "stagnation line" and its relation to the "spray root" and "expanding lamina" analyses. Figure 4:37 shows the geometrical relations that exist on a planing wedge. Knowledge of the nature of the stagnation line has been gleaned from countless underwater photographs. The basic procedure is to rationalize the application of two-dimensional flow based on the pressure distribution resulting from the geometry of flow lines. The wetted semi-width from Wagner's "expanding-lamina" is:

$$C_p = \frac{\pi y}{2} = C_R$$

which is almost the value of the wetted semi-width of the immersing wedge, and the subscripts P, S and R refer to the corresponding widths illustrated in figure 4:37. In defining the stagnation line:

$$C_s = Ky$$

whereby resorting to the spray thickness  $\delta$ , K (the stagnation pressure line) is geometrically derived as a function of the deadrise angle thusly:

$$k \approx \frac{\pi}{2} \left( 1 - \frac{3 \tan^2 \beta \cos \beta}{1.7 \pi^2} - \frac{\tan \beta \sin^2 \beta}{3.3 \pi} \right) \quad (4-23)$$

The location of each line (stagnation, spray root and spray edge) is each in turn associated with some constant  $K_1, 2, \dots$

In determining the peak pressure of a planing wedge, the fact that the peak pressure for the immersing wedge is determined for the case of an infinitely long wedge requires the use of an "effective" deadrise angle which is a function of deadrise and trim angle. Since the velocity normal to the keel is

$$V_R \sin \gamma$$

the expression for  $P_{\max}$  becomes in terms of the "effective" deadrise angle ( $\beta_e$ ):

$$\frac{P_{\max}}{\rho/2(V_R \sin \gamma)^2} = \frac{\pi^2}{4 \tan^2 \beta_e} + 1 = \frac{1}{\lambda_e^2} + 1 \quad (4-24)$$

which is similar to equation (4-18) where:

$$\tan \beta_e = \frac{\pi}{2} \sqrt{\frac{\sin^2 \beta + K^2 \tan^2 \gamma}{(K - \sin^2 \beta)^2 - \sin^2 \beta (\sin^2 \beta + K^2 \tan^2 \gamma)}} \quad (4-25)$$

$$\lambda_e = \frac{2 \tan \beta_e}{\pi} \quad (4-26)$$

For determining the total load on each side of the wedge at a given station figure 4:38a illustrates the total pressure

PRESSURE DISTRIBUTION OVER TYPICAL TRANSVERSE SECTION  
ON WETTED SURFACE OF PLANING WEDGE

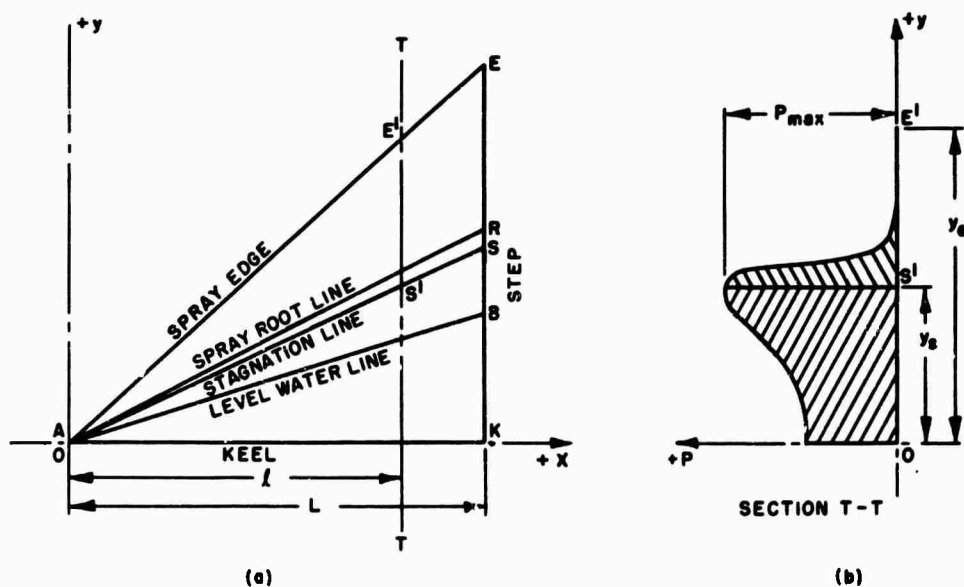


Figure 4:38

as the addition of pressure due to expanding lamina and spray root. By adding the sum of the two integrated pressures, the



average pressure is obtained by dividing by the distance KR in figure 4:37. The total load may then be determined from the average pressure acting over the wetted area. Expressions for lift, drag and average pressure may be analytically determined.

PRESSURE DISTRIBUTION PROFILES ON ONE SIDE OF WETTED SURFACE  
FOR A PRISMATIC PLANING BODY

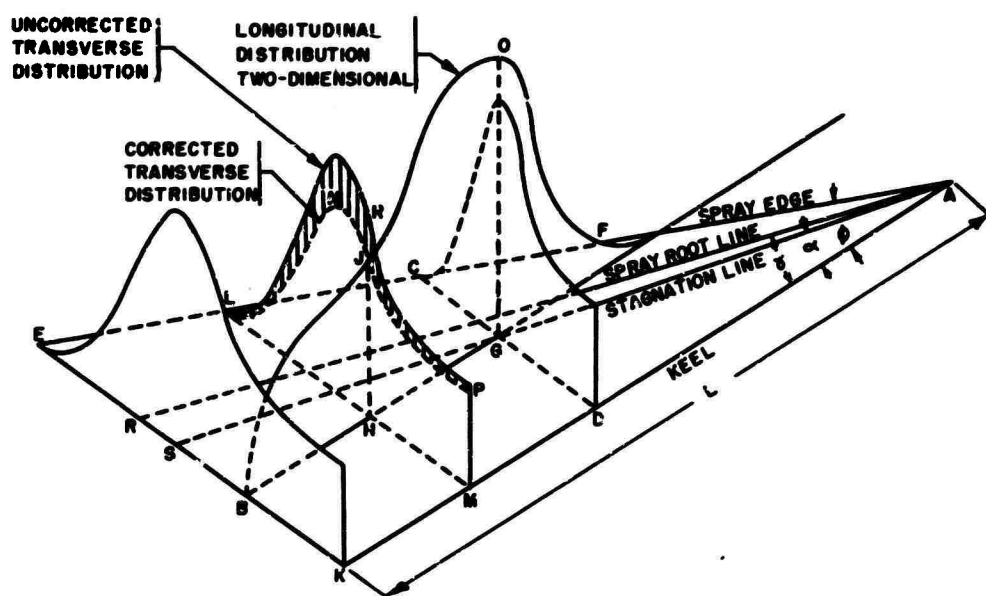


Figure 4:39

Figure 4:39 gives a three-dimensional view of the pressure pattern on one side of a planing wedge. A transverse end loss correction has been applied for the variation of the longitudinal two-dimensional pressure pattern. Figure 4:40 illustrates the end loss at the step.

The information contained in references (28) and (29) is admittedly theoretical with little quantitative testing information to confirm the analysis. With this in mind, several model investigations by the NACA (references (30) and (31)) were made on the pressure patterns produced by planing wedges. Agreement between theory and experiment was fair for trims up to about 15° and consequently an empirical formula:

$$\frac{P_D}{\frac{1}{2} \rho V^2} = \frac{\pi^2 \sin^2 (\gamma + \mathcal{J})}{\pi^2 \sin^2 \mathcal{J} + 4 \tan^2 \beta \cos^2 \mathcal{J}} \quad (4-27)$$

proved a much better fit to the experimental data. Whether or not the magnitudes were correct, the pressure pattern recorded gave the same general shape as that deduced by theory. A typical pressure pattern is shown in figure 4:41.

#### PRESSURE LOSSES AT STEP

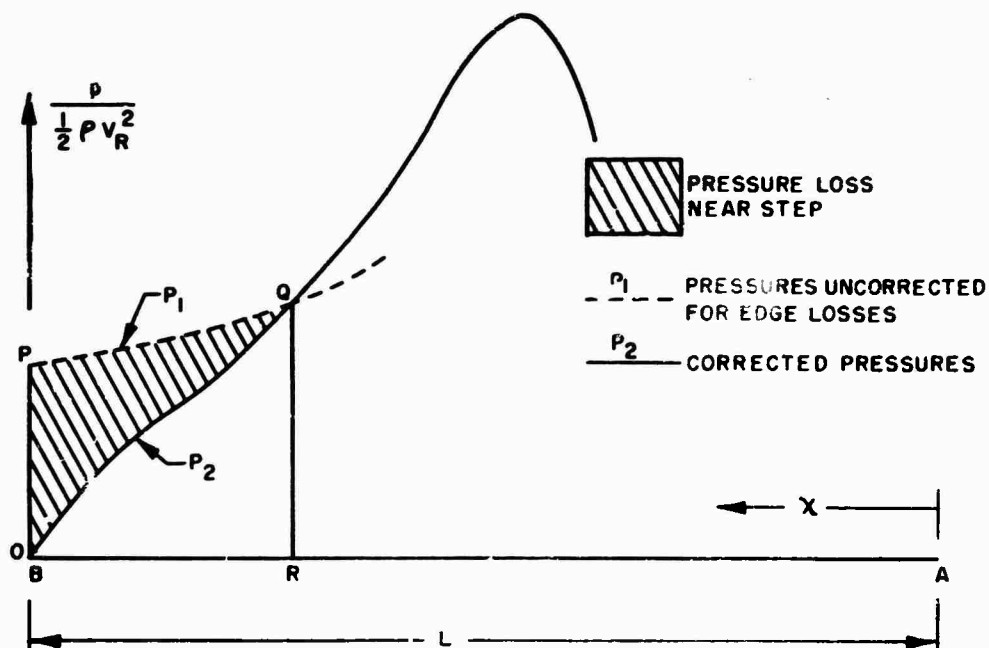


Figure 4:40

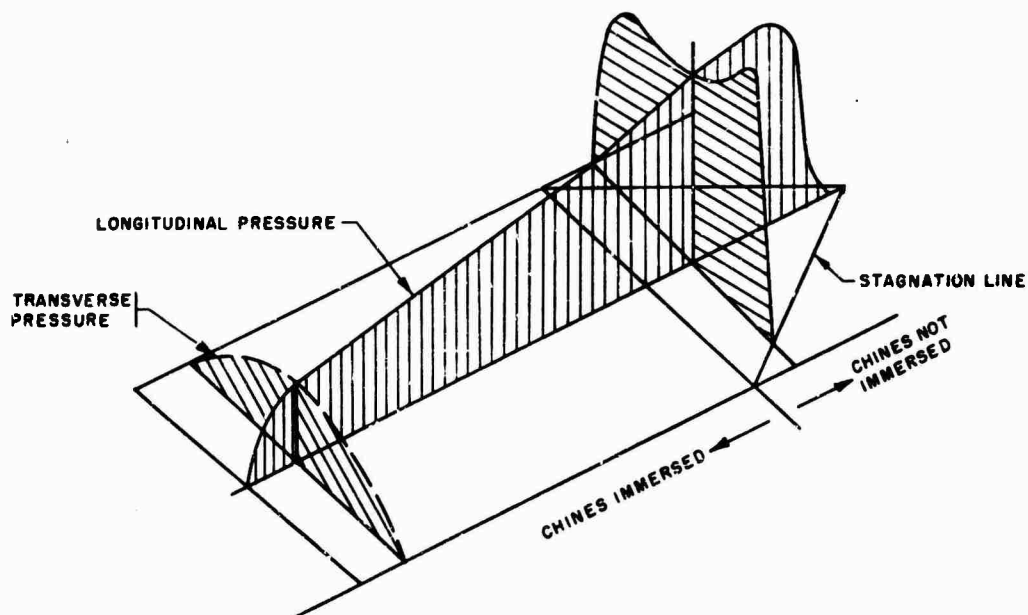


Figure 4:41

Reference (32) reviews both the longitudinal and transverse pressure distributions for a flat plate and a Vee

bottom. A basic relation between impact and planing is presented which may be visualized by reference to the velocity diagram of figure 4:42. The magnitude of pressure in the case of the planing wedge is proportional to the square of the planing velocity  $X$ . The pressure, in the case of impact, bears the same relations to an equivalent planing velocity  $F$  which is defined by the relations:

$$\dot{F} = \dot{X} + Y \cot \gamma \quad (4-28)$$

Therefore, in spite of deviations for end-loss etc., which are considered small, the pressure distribution of a prismatic surface whether in impact or planing can be expressed by the following:

$$\frac{P}{1/2 \rho F^2} = f \left[ \frac{n}{b}, \frac{\lambda}{\lambda_p}, \lambda_p, \beta, \gamma \right] \quad (4-28)$$

The procedure presented in reference (32) is generally an adaptation of theories already presented using charts and the results of previous theories. Similarity between longitudinal pressure distribution on flat plates and Vee-bottoms during planing are noted which simplify the problem. The procedure discussed in the reference is fairly limited to deadrise angles of less than  $30^\circ$ . A generally applicable procedure for use in the entire range of deadrise and trim angles was not covered.

Reference (31) contains a pressure investigation from tests conducted on a prismatic model with a deadrise angle of  $22\frac{1}{2}^\circ$ . It was found necessary, for greater range of agreement, to alter the expression for peak pressure from that presented in reference (29) and modified in equation (4-27) to the following:

$$\frac{P_{p,2}}{1/2 \rho \dot{Z}^2} = \frac{1}{\sin^2 \gamma + J^2 \cos^2 \gamma} \quad (4-30)$$

where the value of  $J$  is determined to be 0.293 for the investigation. In reference (31), using a value of effective deadrise, the expression for peak pressure ( $P_{p,2}/\frac{1}{2} \rho \dot{Z}^2$ ) is compared directly for the non-chine immersed region.

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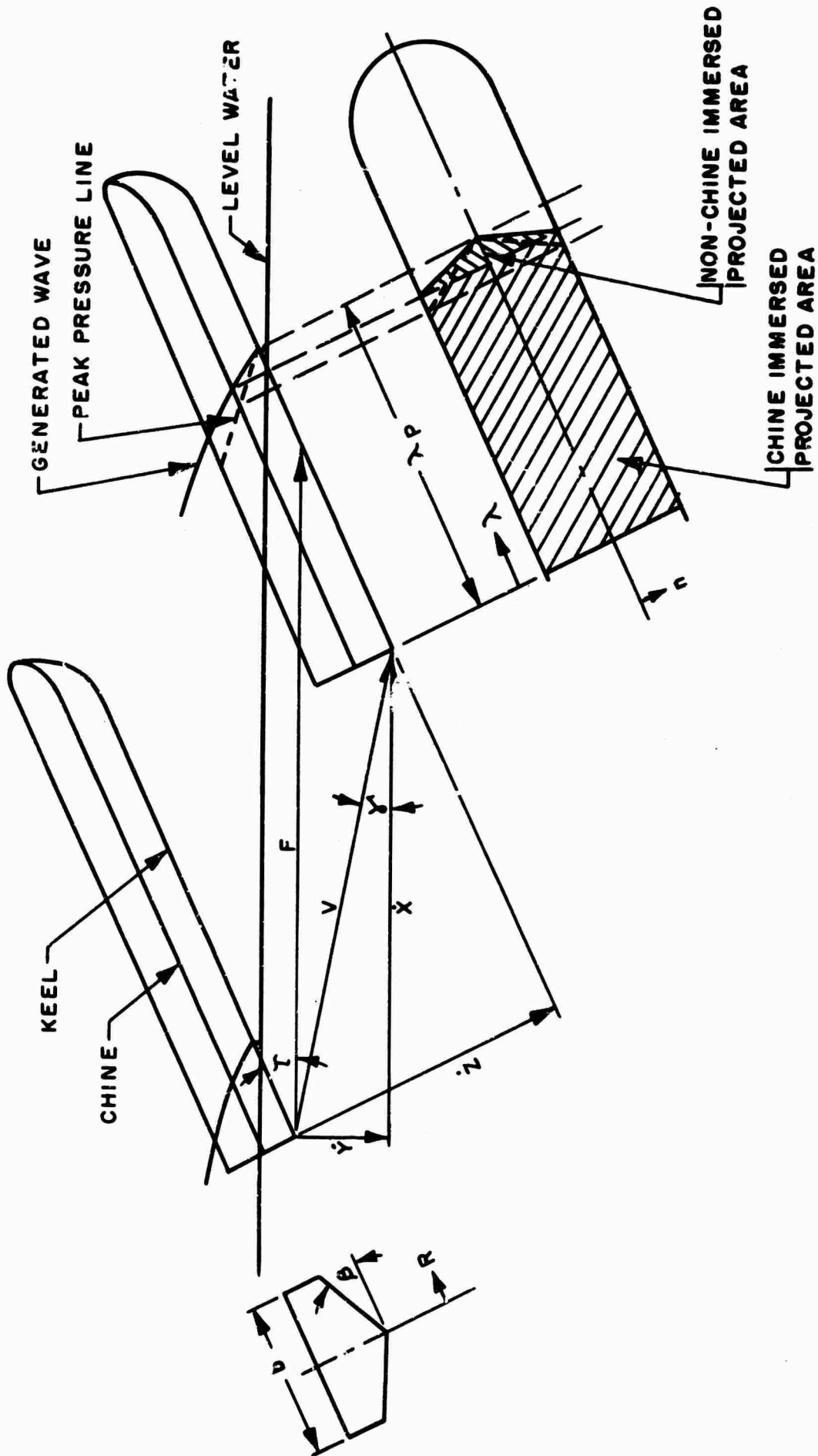


Figure 4:42

#### 4.11.4 FULL SCALE TESTING

In the previous section the problem of pressure distribution was examined and a fairly representative wetted area and corresponding pressure pattern was presented in figure 4:41. The references discussed, indicated that the problem is far from solved and many areas are yet to be investigated. Very little full scale testing has been accomplished. This is due partly to the inadequacy of pressure measuring devices and to the lack of a satisfactory self-contained rate of descent indicator from which the approach parameter can be determined.

Reference (33) was written in 1929 and reported the results of the pressures and accelerations acting on full scale hull bottom in smooth and rough water. The magnitudes reported in reference (33) are of little concern, what is important, is that the results were obtained under actual conditions and the distribution of instantaneous pressure shows surprising agreement with figure 4:41 obtained in model tests.

In recent years one contractor has conducted a full scale investigation of an experimental hull type seaplane containing a rounded keel. The results of this investigation confirmed a few of the basic tenets concerning pressures and loads but fell far short of its goal. Although this plane was tested later at the NATC, the tests did not include a pressure survey.

Full scale testing of the P5M-2 at the NATC, included a pressure survey. Pressure taps and accelerometers were mounted on the hull and oscillograms were obtained during take-offs and landings in wave heights up to 10 ft. Records were so voluminous that NATC was able to report only maximum values at each pressure location during each take-off and landing. A special contract was awarded to analyze these records and the results are not yet available.

Full scale results have indicated one further interesting development. Most model testing was done on prismatic surfaces which, in effect, represented only the forebody of the seaplane. The pressure patterns obtained from these model tests have therefore, not included effect of the presence of the afterbody. The only effect was that of the step itself which caused a drop-off of the longitudinal pressure distribution. Some British results have indicated the presence of negative (less than atmosphere) pressure

areas just behind the main step. This was suspected from early experience with the P5M-1 in rough water. Structural failures in the step area of the P5M-1 indicated that such failures could only have occurred if the bottom plating had been under a negative pressure. The effect of the presence of the afterbody on the pressure pattern requires further investigation.

Pressure surveys on full scale seaplane hulls require extensive instrumentation to record the necessary information. In order to check theory with experiment information on trim and velocity, glide path information will be required. Since no self contained rate-of-descent indicator has yet been developed, Touchdown Rate of Descent Indicator (TRODI) offers the best source of this information, but operations will probably be limited to smooth water impacts when using TRODI.

Although it is always advantageous to correlate the landing impact with the associated pressure pattern, data on loads and strains during impact may also be required. During tests conducted at the NATC on the JRF, information on strut loads was required which could be correlated with rate of descent. The tests were carried out in smooth water and the placement of the TRODI equipment to measure rate of descent was limited to coincide with the most desirable traffic pattern. Many locations were tried but each one limited the available landing area. In view of all the locations used such as breakwaters, beaches, etc., it is felt that the use of a vehicle similar to a YSD provides the greatest chance of success. (A YSD, nicknamed "Mary Anne", is a flat bottomed barge. The barge has a 110V 60C alternating current power-source capable of running the TRODI.) The procedure is to anchor the "Mary Anne" into the prevailing wind with both TRODI and a Mitchell camera installed aft of the starboard beam. The "Mary Anne" is positioned such that there are no restrictions on the traffic pattern to be flown by the test vehicle. An LSO stationed near the recording equipment can provide the pilot with suitable information on the rates-of-sink that are being obtained. Using this procedure, correlations can later be made between the approach parameters and the loads obtained on the oscillograms.

Full scale testing in rough water has been reported in the past on a frequency basis. Recorded acceleration data is analyzed for a given number of take-offs (or landings) and the total number of impacts noted. Once the minimum

value of impact has been determined a frequency chart similar to figure 4:43 can be constructed based on the occurrence of impacts greater or lesser than 1 g.

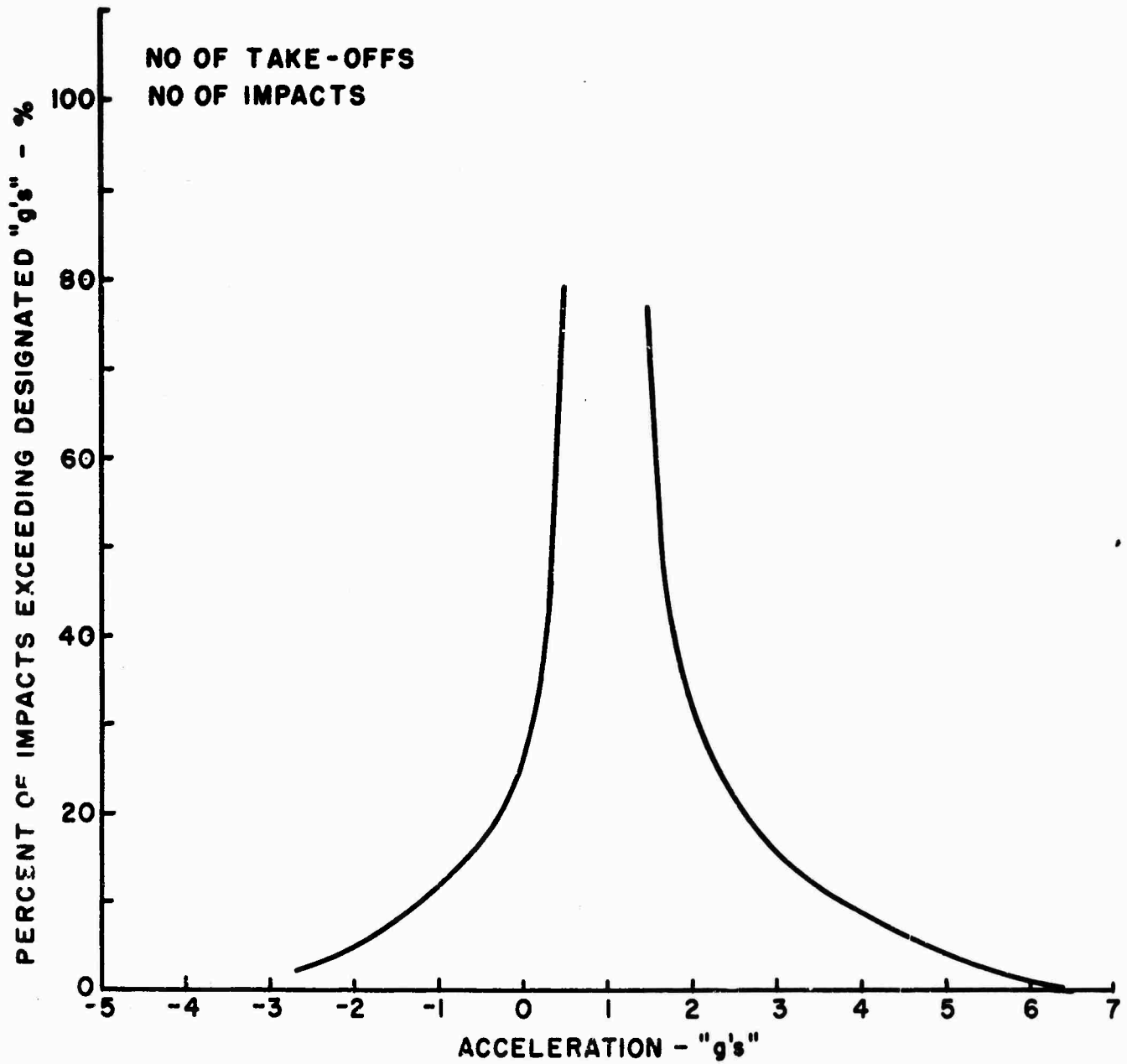


Figure 4:43

#### 4.11.5 ELASTIC RESPONSE

The basic approach in the determination of impact loads has been to assume the seaplane hull to be a rigid body, although it can be intuitively deduced that the seaplane does not react as a solid body.

Several attempts have been made to visualize the elastic response of the seaplane. The simplest approach, as proposed by a British investigator, is to consider a body attached to a planing surface by means of a spring. From the conservation of momentum:

$$(M + M')V_0 = M\dot{y} + (M' + m)\dot{z} \quad (4-31)$$

where

$M$  = Mass of body

$M'$  = Mass of planing surface

$V_0$  = Vertical velocity

$m$  = Virtual mass of the planing surface

and the force in the structure (i.e. the spring) is:

$$M\ddot{y} = -k(y - z) \quad (4-32)$$

An American investigator (Pabst) neglected the mass ( $M'$ ) of the planing surface and wrote:

$$\begin{aligned} M(d^2y/dt^2) &= kf - n\omega \\ m(d^2z/dt^2) &= -kf \\ y - z &= -f \end{aligned} \quad (4-33)$$

where

$n$  = the fraction of the weight remaining after deducting the lift of the wings.

Differentiating equation (4-33) and substituting:

$$d^2f/dt^2 + kf\left(\frac{1}{M} + \frac{1}{m}\right) - ng = 0 \quad (4-34)$$



The solution of equation (4-34) takes the form:

$$f = A \sin \omega t + B \cos \omega t + ng/\omega^2 \quad (4-35)$$

where

$$\omega^2 = k \frac{M + m}{Mm}$$

$$A = V_0/\omega$$

$$B = -ng/\omega^2$$

The solution may also be written in an alternate form:

$$f = Y \sin (\omega t - \beta) + ng/\omega^2 \quad (4-36)$$

where

$$Y = \frac{1}{\omega} \left[ (ng/\omega)^2 + V_0^2 \right]^{1/2} + ng/\omega^2$$

$$\beta = \tan^{-1} B/A$$

The oscillatory character of the deflection ' $f$ ' of the structure supporting the mass, and the resulting oscillation variation of stresses in the structure are the important facts indicated by equations (4-35) and (4-36). This solution indicates the reversal of stress of full magnitude and does not account for damping.

In references (34) and (35) a method similar to the one shown above is used to investigate an elastic airframe. The primary response considered is wing bending simulated by a two mass system connected by a spring having no mass. The two mass system provides representation of the fundamental mode of an airplane wing. The equation of motion, based on hydrodynamic theory, gives the response of the represented mode and the effect on the hydrodynamic force of the primary response. Non-dimensional coefficients are used which are then applicable to a variety of combinations of velocity, weight, deadrise angle and fluid density. The hydrodynamic theory used to predict the instantaneous forces on the hull is based on zero trim change during contact and chines not becoming immersed. The forces computed are those occurring during a single impact and are not successive as might be expected in an actual seaway. The represented structural mode is considered to be devoid of vibration prior to the instant of impact which

would not be the case during successive impacts. Charts of nodal accelerations (the hydrodynamic force in terms of weight) are presented along with charts of oscillatory accelerations which are the model accelerations minus the hull acceleration. In the discussion a correction factor is proposed to account for the fact that the elastic axis is not at the CG. The effect of wing torsion is also discussed. Results indicated that the method constituted a reasonable approach to the problem. However, it was noted that there was a lack of full scale results with which to check theory.

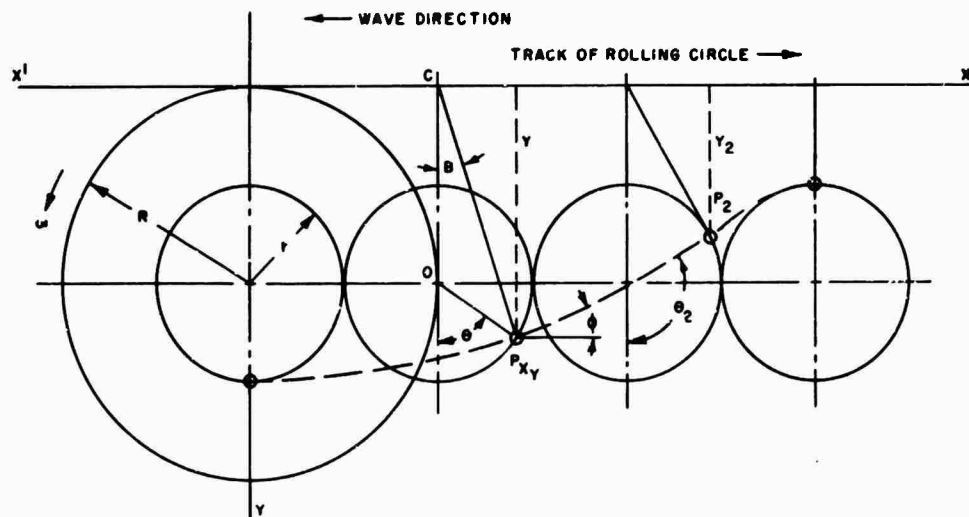
It is obvious that consideration of the fundamental mode alone is not sufficient to define the elastic response of seaplanes. Aerodynamic damping and damping of the hull itself complicates the response pattern. The NATC has not in the past been required to either test or comment on the dynamic response of seaplanes during landing. The problem is one of design. However, for each seaplane tested, the contractor's design data should be carefully scrutinized in regard to impact capabilities.

No study of hydrodynamic theory would be complete without some understanding of the basic nature of wave formation and propagation. To a greater or lesser degree waves are almost always encountered during full scale testing. In fact, the time involved in waiting for a flat calm water condition usually accounts for the major portion of the time allotted for full scale testing. To better understand the background of wave formation, a slightly idealized form of wave motion is presented. As far back as 1802 Gerstner and later Rankine and Froude suggested a possible form of wave motion for infinite depth of water. This is expressed in parametric form:

$$y = b + re^{kb} \cos k(a + ct)$$

$$k = 2\pi/L$$

where  $L$  is the wave length. The quantity ' $c$ ' is the celerity or velocity of propagation. The path of the particle is a circle of radius  $r$  with a wave height of  $2r$  from crest to trough. The velocities of the water particles resulting from the above circular motion are referred to as orbital velocities and the wave depicted by the above motion is that of a trochoid. As shown in figure 4:44, the wave is traced by a



4-92

point "r" located on a disk of radius R as the disk rolls along. The equations of the curve referred to the track are:

$$\begin{aligned} x &= R\theta + r \sin \theta \\ y &= R + r \cos \theta \end{aligned} \quad (4-38)$$

The length of the wave is:

$$L = 2\pi R$$

and the crest-to-trough distance is:

$$H = 2r$$

The slope of the wave surface is:

$$\tan \theta = \tan \phi = dy/dx = \frac{r \sin \theta}{R + r \cos \theta} \quad (4-39)$$

The velocity of wave propagation is:

$$C = \sqrt{gL/2\pi} \quad (4-40)$$

and the period becomes:

$$T = L/C = \sqrt{\frac{2\pi L}{g}} \quad (4-41)$$

As suggested above, an approximation of the water surface by a series of regular trochoidal waves would be an oversimplification. The truth of the matter is that water surfaces vary in locality and with time. Reference (36) contains a selected bibliography on various wave investigations that have been conducted and should be consulted for further information.

Reference (37) is a study of several ocean areas from which charts of monthly and seasonal variations of wind, wave and swell have been prepared. Tables are included which report values of height and swell in terms of cumulative frequencies. All data have been smoothed using the principles of statistical analysis.

Since any given wave train is composed of waves of various heights, reference (37) uses the term "significant" wave height which is defined as "the average of the one-third highest waves". In any wave train there will therefore be waves both lower and higher than the "significant" wave height. The significant height is related to the maximum height by the following ratios:

<u>Wave Height</u>	<u>Relative Height</u>
Significant height	1.00
Average of highest 10%	1.29
Mean height of all waves	0.64
Maximum height	1.87

Rather than represent the sea by some arbitrary number representing a sea state, both the sea and swell as defined in section 1.3 are shown separately. This is because the appearance of the sea surface depends on the directions of travel of the seas and swells, their periods, height and phase relationships. Depending on these mutual relationships, the wave trains can interfere to reinforce or reduce each other thereby producing greater height on an almost flat sea.

The interaction of wave trains referred to above, causes the wave pattern in the open sea to be best characterized by its randomness and certainly far from the trochoidal pattern referred to at the beginning of this section. Reference (38) contains a statistical approach to the operations of sea-planes in the open sea. A general background to the statistical description of wave patterns yields several formulae used to describe wave characteristics:

$$H_{\max} = 1.5 \sqrt{\text{Fetch}}$$

For unlimited wind duration and fetch:

$$H_{\max} = 0.023V^2$$

which has also been presented empirically as:

$$L_{\max} = 1.1 V^2$$

The wave steepness (used here as  $H/L$  instead of  $L/H$ ) has been determined to depend on the ratio of wave velocity which has been termed the "wave age". As the wave age increases the waves become more flat. The relationships between age and steepness has been fairly well borne out by observation.

In order to characterize a sea surface and reduce the randomness in the wave profile, statistical correlation

functions are introduced. Specifically, an auto-correlation function is defined from which a correlogram may be plotted. If the surface is completely random, the correlogram will appear as a damped exponented curve. The major portion of the correlogram is the cyclic component which represents the swell while the residue represents a series of local disturbance which die out rapidly.

The statistical approach to wave analysis has been suggested by several investigators and the adviseability of its use adequately illustrated from countless observations. The difficulty of determining wave heights has been born out many times during the contractors attempts to comply with seaplane landing requirements. Rough water characteristics are demonstrated by requiring a stated number of landings and take-offs in waves of specified height. Unfortunately although the maximum wave height may be specified by contract, there is often a conflict concerning the manner in which the requirement has been met. In view of the wave discussion presented above, instead of specifying maximum wave height, use of the equivalent height would be more realistic.

On at least two occasions, the NATC has been required to operate seaplanes in rough water during which, knowledge of the wave height was required. Figure 4:45 shows a wavemeter which may be used to indicate wave heights. The meter is simple and has given fair results. By timing with a stop watch and noting individual wave heights it should be possible to define the wave train. The occurrence in the wave train of an isolated 6 ft wave cannot logically be used to satisfy a requirement for operations in six foot waves. When wave information is required during rough water operations,

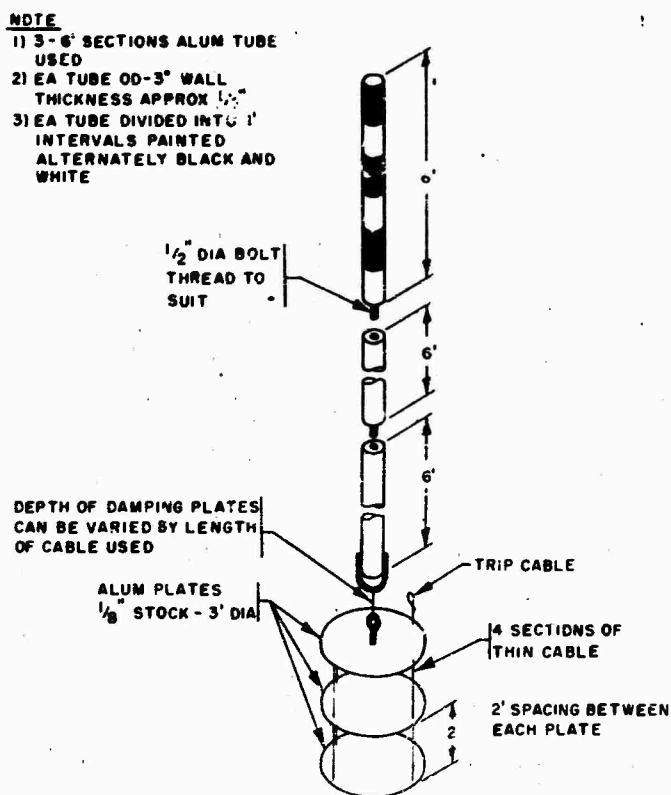


Figure 4:45

careful observations must be made at the site of the operations. An observer on a surface craft should be equipped with an anemometer and a stop watch. The following information should be recorded:

- a. Sea conditions and direction of movement
- b. Wind speed and direction
- c. Swell condition and direction of movement
- d. Height and period of waves
- e. Definition of the wave train if possible.

Statistical wave information has been used in references (38) and (39) to estimate the strength requirements of seaplane hulls for both routine and rough water operations. The conclusion has been made that the number of variables that must be considered for rough water considerably exceed the variables for smooth water impacts.

Theoretically, rough water impacts can be predicted from smooth water technique, by adjusting the trim angle to account for the angle of the wave flank on which the landing is made. In other words rough water impacts can be predicted by using an "effective" trim angle. Unfortunately full scale results in rough water are extremely limited. Model testing has indicated that landing a seaplane in rough water is a random process where the flank of the wave can be hit only a certain percentage of the time. Therefore, the seaplane landing variables and the wave variables are combined to form a group of variables that are particularly amenable to statistical solution. When operations in rough water are required, the information contained in reference (40) should be consulted in planning test work.

#### 4.11.7 SEAWORTHINESS

In section 4.11.1 the problem of controllability was suggested as the second of two parameters limiting the seaplanes performance in rough water. The hydrodynamic tests listed in section 4.2 to 4.9 were for the most part required to be performed in smooth water. In discussing several of the tests, brief reference to the qualitative aspects of rough water testing was made. The controllability evaluation is usually qualitative and therefore, the general procedure is to concurrently test in both smooth and rough water to determine operational limits.

Spray can have serious consequences when its effect is aggravated by the action of waves. Under such action, bow spray which may not ordinarily be of any consequence, can hamper vision and produce other deleterious effects. Low speed and high speed runs should be made at various angles to the wind and wave in order to evaluate the effect of rough water.

Lateral and directional control may also be evaluated by moving the seaplane at various angles to the wind and wave. For seaplanes the limit of operations may be set by the ability of the seaplane to turn in or out of the wind due to wave action on the wing tip floats. Turning times may be measured; however, the determination of diameter based on photography may be impossible in a rough sea as explained in preceding paragraphs.

Longitudinal control in waves may be critical due to wave action placing the hull dangerously near the limits of stability. This situation can be aggravated by poor elevator effectiveness. However if take-offs can be made into the wind, the additional mass-flow over the elevators may improve the situation.

It is possible to measure take-off times in rough water and perhaps even take-off distance, provided suitable photography is available. The take-off time is a function of the resistance. In references (17) and (18), tests have indicated that the resistance of a seaplane hull in waves is appreciably increased over the same hull's resistance in smooth water. A rise in the resistance would of course cancel the effects that would be expected from the additional mass flow over wing and tail.

Controllability is also evaluated during load-measuring operations. A high measure of controllability will



undoubtedly aid the pilot in making less severe landings. A procedure for using reverse-pitch with reciprocating engines just prior to touchdown, has proved that landings of lesser impact can be made in rough water. Reference (40) discusses some rough water techniques that have been developed by the U. S. Coast Guard.

## CHAPTER 5

### GENERAL

#### 5.1 Instrumentation

##### 5.1.1 Background

##### 5.1.2 Measurement Methods

##### 5.1.3 Instrumentation System Installation Methods

###### 5.1.3.1 Internal

###### 5.1.3.2 External

##### 5.1.4 Sample Installation

##### 5.1.5 Data Reduction

#### 5.2 Seaplane Thrust Stand

#### 5.3 Seaplane Handling

#### 5.4 Future Developments

## 5.1 INSTRUMENTATION

### 5.1.1 BACKGROUND

The instrumentation installed for hydrodynamic testing must be sufficiently coordinated ahead of time. Therefore, plans for instrumentation should be formulated at least in the programming phase. Planning for the instrumentation of Demonstration Aircraft is required by MIL-D-8708. PTR projects may require liaison by NATC prior to contractor tests and subsequent delivery to NATC. Some projects will require that NATC plan and install all or a portion of the instrumentation. Required planning is implemented by means of a conference between representatives of the Instrumentation Branch and cognizant project personnel. During the conference, the Instrumentation Specification Sheet is prepared which lists by item No. the measurement desired, the type instrument, the calibrated accuracy, the range and whether the instrument is provided by the contractor or instrumentation. All questions concerning instrumentation should be anticipated and answered if possible at the conference.

Planning and programming should be used to the utmost in order that the proposed instrumentation be complete and commensurate with the testing objectives. As suggested in previous sections, figure 4:1 will serve as a guide to indicate the data that may be recorded for each hydrodynamic characteristic tested. Depending on the types of tests to be conducted a chart similar to figure 4:1 may be made which is applicable. Each section in this manual from 4.2 to 4.9 suggests the quantities that are amenable to measurement for each test. The sections that follow attempt to indicate the installation and instruments that will best record the recommended data. The extent of quantitative data to be recorded during any test must be realistic. A requirement for instrumentation over and above that actually needed can do nothing but create an undesirable workload.

### 5.1.2 MEASUREMENT METHODS

The following is a general discussion of the methods used in the selecting and placing instruments to be used for the collection of data during tests. The treatment is general and slanted toward the applicability of instruments for hydrodynamic testing.

#### ACCELEROMETERS

##### Linear

The type of accelerometer most generally in use is the unbonded strain gage. The basic element is a transducer consisting of four filaments electrically and mechanically symmetrical. The accelerometer has two elements which are stationary and two elements which can move (the armature) when subjected to some load. The change in length of the wire in the armature causes a change in resistance which is measured by a wheatstone bridge. Several types of strain gage accelerometers covering various ranges and frequencies are available.

The accelerometers are mounted to obtain vertical and horizontal accelerations in a direction perpendicular and parallel to the axis of the seaplane (not direction of motion). Therefore when the seaplane is landing at some angle of trim the accelerations read in g's are in error by the amount  $\cos \gamma$ . This error is considered small under normal conditions. Vertical (normal) accelerations are usually required at the CG, nose and tail. In rough water work, normal accelerations may be required, in addition to those already stated, at wing tips, floats, engine mounts and at the pilot's position.

##### Angular

Using the basic principle of the strain gage transducer, the angular accelerometer employs a rotor pivoted at the CG and restrained from free rotation by a spring. A constant angular acceleration produces a constant deflection which is then read as a load. Some accelerometers employ a liquid mass instead of a rotor. As with the case of linear accelerometers, the angular accelerometer comes in various ranges and responses.

Angular accelerations are usually installed at the CG position to measure accelerations in pitch, roll, and yaw.

## ATTITUDE

### Trim Angle

The simplest system for recording trim angle is the NACA visual trimscope. This instrument consists of a columnated telescope containing graduated lines representing degrees. The scope is installed so that the angle of the hull, referred to the keel base line, is measured from the pilots' compartment. This instrument theoretically requires a horizon at infinity, and errors are introduced as the usable horizon moves closer to the plane. The instrument is also unusable when testing under no-horizon conditions. Only instantaneous readings can be made. Time histories of trim can be made only by a correlation of voice tape recording.

The Gianinni vertical gyro provides excellent time history information without the errors associated with the visual readings of the NACA visual trim scope. Relative trim angles over the range of operations are easily obtained. However, in order to obtain accurate absolute trim angles with respect to the keel of the hull, the instrument must be exactly and accurately installed. The Gianinni vertical gyro is best recorded on an oscillograph. On one occasion the output of a Gianinni gyro was recorded on a microammeter dial calibrated for trim and installed on a photopanel. The installation was not satisfactory.

One alternate method consists of a standard turn and bank gyro mounted along the longitudinal axis of the seaplane. As the gyro moves, a signal is transmitted to a dial indicating degrees up or down. Trim recordings using this installation on a photopanel have been quite successful.

In all recordings of trim it is essential that the trim of the hull be measured from the keel base line. If the contractor, however, has used some other reference line, the system used by NATC should be such as to provide direct comparison with the contractor's data.

### Heel Angle

Heel angle indications are provided by an oil-damped pendulum mounted transversely on the flight deck. Pendulum motion is transmitted electrically to a remote indicator dial. This instrument has in the past generally

been used during spray tests in order to apply the corrections specified in section 4.3.2.1. The instrument is particularly suited to constant speed spray runs since data is usually manually recorded. If, due to improved data reduction techniques, it is felt that automatic recording can be used, the heel angle indicator above can be replaced with either a Gianinni vertical gyro for reading bank angle or with a modified turn and bank indicator as discussed previously. Such an installation will provide a time history of the heel angle.

### CONTROL FORCE

Control force information is not always required for hydrodynamic tests. However, time histories of the three major control forces recorded during take-off or landing can provide desirable information. In one case the upper limit for longitudinal stability was set at the limit of the pilot's ability to hold full-up elevator at forward CG. Under such conditions the elevator force required should be known. Likewise, during directional stability tests the force exerted on the rudder, when known, can be used to determine the amount of hooking moment. Unless otherwise specified, lateral force information is the least required.

Both the rudder and elevator force instrumentation will probably already be included in seaplanes undergoing BIS trials. The nature and extent of other tests will govern the need for control force instrumentation not otherwise needed. The installation under any conditions will be the standard transmitter and indicator system.

### ENGINE POWER

Engine power instruments are chiefly required in order to supply information on power output. For reciprocating engines the sea level BHP may be approximated from RPM, MAP and OAT by use of manufacturer's engine calibration curves. This system may not supply the accuracy required for power determination, especially if the value of hydrodynamic resistance is being determined from full scale accelerated runs. Provided the engine is so equipped, reliable BHP and thrust information can be obtained from a torquemeter. Various engine models may have gages giving a direct indication of BMEP.

## FUEL

The primary reason for installing fuel indicators is to determine changes in gross weight during the course of testing. This information can be determined by using any of the following:

- a. Rate-of-flow meter
- b. Totalizing flow meter
- c. Aircraft fuel quantity gage

The first two methods require accurate calibration. It is considered that a simple fuel quantity gage will provide the information required for gross weight determination to a sufficient degree of accuracy. A simple calibration can be made by filling the seaplane's empty tanks with fuel metered from a known source. During the course of filling, the aircraft tank reading and the fuel delivered are simultaneously read at even increments of fuel delivered. A fuel quantity calibration curve can then be plotted.

During tests, fuel readings can be made at some increment of time (every 15 min) and a fuel consumption curve may be plotted for each flight. Another procedure would be to take fuel readings prior to each take-off, landing, or special maneuver.

## MISCELLANEOUS

In any instrumentation installation, there will be many miscellaneous instruments required that are designed to supply additional information. For instance:

Event Markers are used in an oscillograph to mark various points of interest during the course of the run such as take-off, ski unporting, ski submergence, etc. A button may be installed such that when the button is depressed a trace on the oscillograph is displaced thereby marking the point of interest.

Correlators are used to relate the records of separate recording systems. An example of this would be the "blip" produced on an oscillograph record each time a camera installation takes a picture.

Counters are usually used in a photopanel to indicate frame or run number. Frame numbers need not necessarily

be installed on the photopanel but can be located at some other point and recorded on the pilot's card as "run No. 1 - frames 24-64".

Timers are usually installed in a photopanel in the form of either a 24-hour clock or a sweep second stop watch or both.

## POSITION

### Main Control Surface

If the hydrodynamic tests being conducted are part of BIS trials, the instrumentation will include position indicators. Of the three major control position indicators (i.e. elevator, rudder and aileron) the elevator control position is the most important and for the majority of special hydrodynamic PTR projects, both rudder and aileron position indicators may be left out.

As seaplanes with greater performance capabilities are developed, the longitudinal control system becomes more complicated. Older seaplanes contained an elevator and tab connected by mechanical linkage to the pilot's station. Under this simple system, the elevator position indicator was the only measure of longitudinal control movement required. In the case of the R3Y not only the elevator position, but the position of the spring-loaded tab as well was required. With the development of longitudinal control systems such as installed on the P6M, it may be required to know the control column, stabilizer and elevator positions simultaneously. That portion of the longitudinal control system which, when recorded will provide the greatest information will be dependent on the nature and extent of the tests.

Whatever portion of the control system is instrumented, the installation consists of a variable resistance position transducer placed as closely to the control surface hinge as possible. The control movements are equally capable of being recorded on oscillograph or photopanel.

## PRESSURE

The pressure transducer consists of the basic unbonded strain gage element connected in such a manner that pressure per square inch against a plate or diaphragm changes



the electrical resistance of the moveable element. This resistance is then calibrated in terms of lb/in<sup>2</sup> per unit of diaphragm movement.

The principal use of pressure instrumentation installed in the hull bottom of a seaplane is for impact load information. The installation of pressure transducers in a hull bottom must be watertight and placed within the correct tolerance if other than a flush mounting is required. Many types of pressure transducers are available with a variety of range and frequency response. It has been demonstrated from actual tests that the measurement of peak pressures during impact landings is quite difficult. The transient effects of pressure are such that the transducer rarely records the correct magnitude but rather some lesser value than peak pressure. The pressure pattern created on the hull bottom during steady-state planing however, is fairly well represented by the value obtained from the transducers. Transducers are also difficult to maintain and require frequent replacing. For a hull bottom pressure survey, transducer pressures are recorded on an oscillograph.

#### STRAIN GAGE

Strain gages are usually bonded to some surface in a bridge for each loading direction required. Strain gages have been used in various locations on the hull in order to obtain information on stresses and strains existent during various maneuvers. One project at NATC required the instrumentation of a ski strut in order to obtain information on side load, drag load and bending. Due to the difficulties, mainly in calibration, the strut was instrumented and calibrated at ASL (Philadelphia). The bonding of strain gages for underwater application became quite a problem. Reference (21) contains the results of a study on the waterproofing of strain gages for underwater use. The David Taylor Model Basin has apparently had success in this line. Convair also had occasion to use strain gage waterproofing for instrumentation on the F2Y. They too apparently arrived at a suitable method of application. No one method appears best. It is recommended that when underwater strain gages are required, all available literature be consulted for the latest "state of the art".

## VELOCITY

### Angular

Angular velocity about any one of the three major axes is determined by a rate gyro oriented for the specific axis. The gyro is electrically driven and when a force is exerted the gyro precesses. The precessing force is opposed by a spring restraining the gimbal. The gimbal displacement is a measurement of the angular velocity which is then transmitted electrically.

Recordings of angular velocity have seldom been used in hydrodynamic testing. However, they are included in the event that their use at some later date is felt necessary.

### Linear

An airspeed system separate from the ships service system should be installed for best results. This requirement may be filled by a wing boom with swivel head. The airspeed indicators used should be of the sensitive type. If the speed range of the test vehicle is such that high speeds (greater than 150 kt) are anticipated, a two-scale installation will be required. Both the pilot's and the photopanel indicators can work off the same system. However, to minimize instrumentation, the pilot's sensitive airspeed indicator can work from the ships service system, while the photopanel or oscillograph indicator can work from the wing boom system.

The British have used, with success, a keel tube for recording total pressure while measuring static pressure from an isolated tank. This tank must be close to the indicator and be insulated to eliminate temperature effects. The static tank contains a shut-off valve which vents the tank to the atmosphere prior to beginning a run. The tank is then shut off and the static reference remains fixed. Take-off runs to an altitude of approximately 50 ft will give satisfactory results. Airspeed readings above this altitude will not be accurate because the static reference is at sea level. For each subsequent run the tank is vented to the atmosphere and then shut off. One such installation was tried at NATC without success. However, it is felt that the system has merit and should be investigated further.

For oscillograph recording, a pressure transducer is required for velocity recording. The transducer changes

air pressure into electrical impulses which are transmitted to recording galvanometer traces. Generally these pressure transducers can not work accurately on an oscillograph at airspeeds less than 30 kt. The airspeed transducer calibration has the added disadvantage of being non-linear.

The waterspeed indicator is one of the most important pieces of instrumentation used for seaplane testing and yet it is probably one of the least used. There are several problems connected with the use of waterspeed indicators, the most important of which is the location. For hull type seaplanes a ram pressure of total head pick up is usually installed in the vicinity of the step. For normal minimum impact landings the step is usually the first part of the hull to touch water. Consequently, when touchdown waterspeed indications are desired, the step provides an excellent location.

With short afterbody hulls the step area is considered to be always immersed under all conditions including that of maximum and minimum trim angles. However with long afterbody hulls, a distinct possibility exists that at high trim angles planing can occur on the afterbody alone. Under such conditions, a pick-up head would be required on the afterbody as well as in the step area. The afterbody pick-up can be considered to give satisfactory results when located  $2/3$  of the afterbody distance forward of the sternpost.

Instrument error calibrations for waterspeed indicators follow a standard procedure. However, no calibration, corrections have been made for position error as is done for an airspeed calibration. Not too much is known of the flow field on the bottom of seaplane hulls during various speed regimes. Also, little is known concerning the depth of turbulence on the bottom which would govern the distance away from the hull that the pick-up head is placed. The waterspeed indicator is usually checked by noting the reading on a calibrated airspeed indicator and correcting for the existing wind component in the direction of motion. This corrected reading is checked against the waterspeed indicator reading. A discrepancy of  $\pm 1-2$  kt has been sufficient reason to conclude that there is no appreciable position error.

The above appears true for low trim angles and higher speeds but is open to question at lower speeds and high trim angles. The point to be considered is that accurate waterspeed information prior to hump is seldom required in

seaplanes of the hull type. Consequently a computation of position error may be superfluous. However for ski type seaplanes low speed information is often of paramount importance.

A calibration of a water velocity instrument might be accomplished in the low speed range by a speed boat. Or perhaps a shore-located Fairchild flight analyzer might be used for the entire speed range. For ski equipped seaplanes, the pick-up head can be installed at the trailing end of the ski. If equipment is located at the trailing end, the pick-up head can be located to a maximum of  $1/3$  the distance forward from the trailing end of the ski. To date (January 1958) NATC has never tested a true hydro-foil seaplane and consequently, the problem of the location of the waterspeed pick-up head has not been encountered. The governing principle of location is similar to airspeed total head pick-up. That is, the pick-up should be located as far as possible away from turbulence and transient pressure fields.

### 5.1.3 INSTRUMENTATION SYSTEM INSTALLATION METHODS

#### 5.1.3.1 INTERNAL

Frequently both an oscillograph and a photopanel will be required to record the desired data. In such a case, a decision must be made to have both installations actuated by the same switch or separately actuated. Both common and separate switches have been used. Under either single or combined actuation a camera correlation is required. As long as there is satisfactory correlation between the photopanel and the oscillograph it is not too important how the units are actuated. During rough water work it is convenient for the co-pilot to be able to move only one switch in order to begin automatic recording.

In any instrumentation system, serious consideration must be given to the power requirements of the system. Most seaplanes, when operating on the water, use engine power settings much below that required for rated generator output. When this condition exists some type of auxiliary power plant is required to supply power for the operation of hydro-flaps, propeller reversing and radio when generator output is low. If the system has a tendency to be overloaded during maneuvers on the water, the addition of instrumentation may well be beyond the capabilities of the auxiliary power plant. The installation of standby batteries or a second auxiliary power plant may be required. When Gianinni vertical gyros are used the voltage supplied must be within a very small tolerance or the gyro will indicate falsely.

#### OSCILLOGRAPH

A typical installation consists of the oscillograph, an amplifier, a power supply and a bridge balance box. Power for instrumentation may be taken from the airplane electrical system or from a separate source. The oscillograph consists of galvanometers which record on a moving roll of sensitized paper. Proper selection of the galvanometer circuitry will ensure proper damping and linearize frequency response over the expected range of frequency to be encountered. A small mirror is attached to the moving coil of the galvanometer which deflects a fine beam of light laterally to a moving strip of sensitized paper. This provides a time history of recorded events by moving across timing lines spaced at intervals of 1/100 of a second. Paper speed may be varied and the width of the

paper can be anywhere from 2 to 12 inches. As many as 36 channels can be used depending on the model installed.

The oscillograph is usually equipped with a master switch which when turned on, lights a green light. The only remaining step prior to recording is to uncage those gyros in the system which are part of the recording sequence. When the gyros have been uncaged, the "operate" switch is actuated and automatic recording begins and continues until the switch is turned off. Generally included in the mechanism of the oscillograph, are provisions for automatically obtaining and marking on each trace in turn a trace deflection which can be recorded at the beginning and end of each oscillograph roll or at the beginning of each run. The trace deflection mentioned above is standard and is referred to as the "R-cal" and represents in inches the equivalent load for which the oscillograph galvanometer has been balanced.

A "jam" light is normally installed which automatically lights whenever a roll is jammed. The light may also indicate when the roll has been expended.

#### PHOTOPANEL

A typical installation consists of a light-proof frame in which the recording instruments, a light source for satisfactory photography and the camera itself are installed. Care should be exercised that the camera intended to be used will be able to withstand any expected inertia effects. One of the principle advantages of a camera installation is that it can be tailored to fit a variety of available spaces. The camera should be equipped with selective exposure rates and counters indicating film used and remaining. The usual correlation provisions for use with an oscillograph is a "blip" which marks the oscillograph trace every time the camera shutter opens to take a picture.

### 5.1.3.2 EXTERNAL

External instrumentation may be required during the conduct of hydrodynamic tests. Such instrumentation could include:

- a. TRODI mirrors installed outside the plane.
- b. Externally mounted camera on some part of the airplane, either to photograph spray or the reaction of a structural member.
- c. Automatically triggered event lights actuated or recorded by outside cameras.
- d. Fairchild or Mitchell cameras installed on shore or on a nearby barge.

Most of the above are self explanatory. Item a. refers to rate of sink determination as discussed in section 4.11.4. Item b. has been used on several occasions without notable success. In one case a camera was mounted on a wing tip float in order to photograph the spray pattern on the hull. The most serious deficiency was the lack of field of view. From the float it was impossible to obtain a sufficient angle to photograph an adequate length of the hull. Spray and acceleration effects contributed to poor results. Item c. is particularly favored by the British as a means of correlating the cameras they use for photographing hydrodynamic tests. Although NATC has never had occasion to use these devices, it is felt that in some cases, when recording from shore cameras, an automatically triggered light such as a photo-electric cell, would be of assistance. Item d. has been used in the case of seaplanes for measuring rates of sink and for attempting to calibrate waterspeeds. The rate-of-sink installation is discussed in section 4.11.4. In one case, a Fairchild flight analyzer was used to obtain the average value of waterspeed during a spray investigation. The camera was installed on the Flight Test breakwater and the seaplane made constant speed runs off shore between a line of buoys used as position markers. This system has already been mentioned as a source of waterspeed and airspeed calibration.

#### 5.1.4 SAMPLE INSTALLATION

Instrumentation depends on the nature and extent of the testing to be done. For special tests, special instrumentation will have to be considered and perhaps specially designed.

Instruments used during hydrodynamic tests have different recording characteristics. Therefore both an oscillograph and a photopanel may be required as well as instrumentation installed on the pilot's panel. Below are listed instruments which might be installed for general hydrodynamic testing. These instruments have been grouped according to method of recording. Additional instruments which may be required on the pilot's panel are also listed.

##### OSCILLOGRAPH RECORDER

- a. Trim angle
- b. Vertical accelerometer
- c. Longitudinal accelerometer
- d. Elevator position
- e. Roll angular accelerometer
- f. Pitch angular accelerometer
- g. Airspeed
- h. Waterspeed
- i. Rudder position
- j. Heel angle
- k. Elevator force
- l. Pitch rate of change.

##### PILOT'S PANEL

- a. Elevator position indicator
- b. Waterspeed indicator (sensitive)
- c. Airspeed indicator (sensitive)



d. Gianinni vertical gyro - visual indicator

PHOTOPANEL

a. Tachometer (2) R & L engine

b. MAP gages (2) R & L engine

c. Torquemeter pressure gages (2) R & L engine

d. Outside air temperature

e. Fuel totaling or fuel remaining

f. Wing flap position

g. Clock (24 hr)

h. Stop watch

i. Flight and run indicator.

### 5.1.5 DATA REDUCTION

Each section pertaining to a specific hydrodynamic test specifies the data to be collected, the method of test and the method of presenting the data. The manner in which the data is to be reduced is, for the most part, only implied.

Special thought should be given to data reduction requirements since an extensive number of time histories are usually recorded during a hydrodynamic test. A program of large scope can compile records that may be beyond the capabilities of the data system to process in a reasonable amount of time.

Prior to the initiation of semi-automatic and automatic data handling methods in the Flight Test Division, one rough water project conducted by NATC generated so much data that it was impossible to tabulate and correlate. The time histories of thirty six channels of pressure and accelerations were needed for each of 36 landings and take-offs. As a practical compromise, maximum and average values only were reported and the accumulated records were analyzed under a special outside contract.

Three data handling systems may be installed in the airplane i.e. magnetic tape, oscillograph and photopanel. Each has its features and limitations and any one or all should be considered to handle the data. A detail discussion on data handling methods of the Flight Test Division is contained in report FT03-114, J15-5 of 12 April 1957.

External instrumentation includes both photographic and electronic units to record sink speed, navigation speeds and spray patterns. The data reduction procedures for these items can be handled on the semi-automatic equipment of the Data Analysis Section. A check with that Section on procedures is desirable prior to performing the test flights.

## 5.2 SEAPLANE THRUST STAND

A special thrust stand for seaplanes is provided on the beach between Fishing Point and the East Seaplane Basin. A sketch of the general arrangement of the thrust stand site is shown in figure 5:1. The thrust stand consists of a

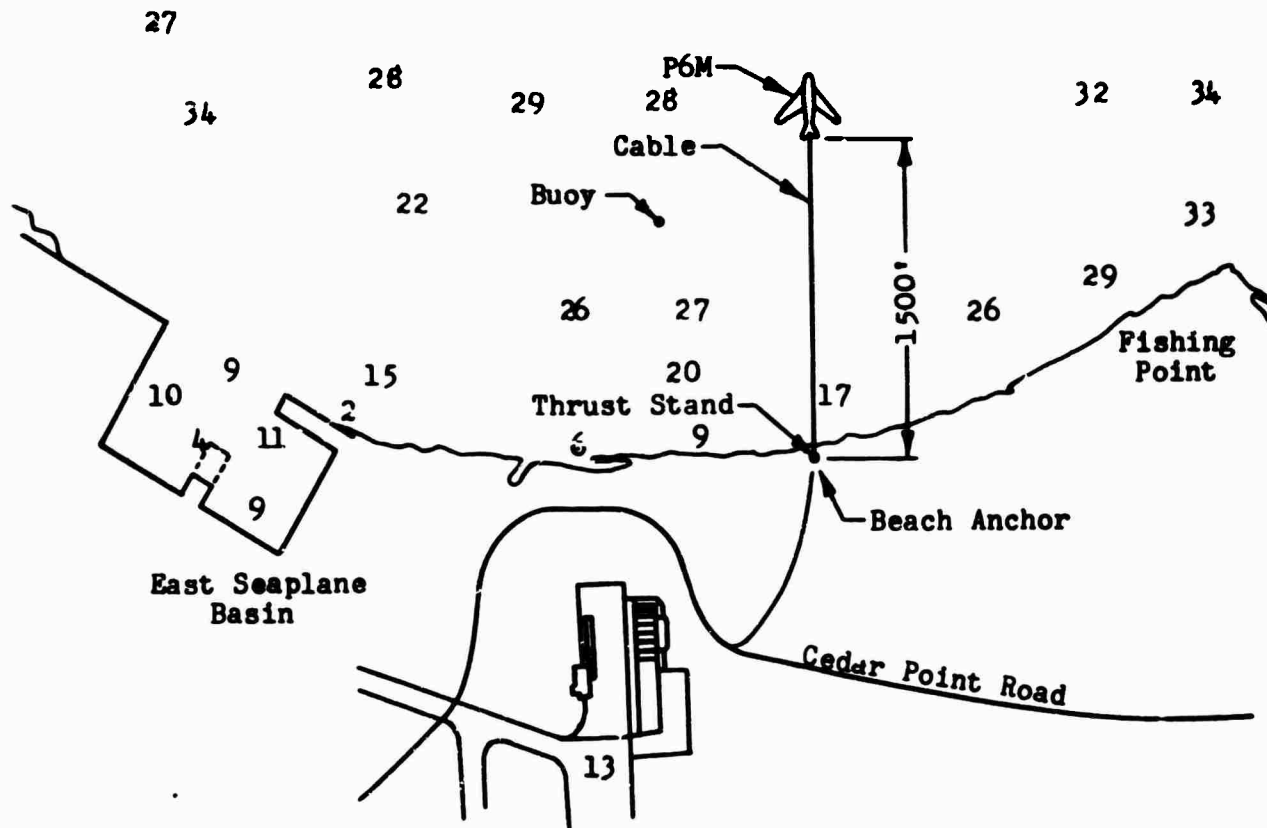


Figure 5:1

removable Emery Cell secured to an anchor on the beach and attached by a 1500 ft cable to a special link on the airplane. To minimize the catenary, the cable remains under water and is supported near the water surface by attached floats (inner tubes). The thrust stand can handle airplane thrusts up to 80,000 lb to an accuracy of 0.1% of full scale.

A special attachment is required on the airplane to provide a means of securing the airplane to the cable. It is essential that this hook-up provision be stronger than maximum airplane thrust. The securing provision need not be a single fitting, but the fitting(s) should be located on the airplane in such a manner that a minimum fuselage pitch is induced when the airplane is turning up at the thrust stand. The requirements for the airplane fitting should be established at the Instrumentation Planning Conference.

It is recommended that the seaplane thrust stand be used between tides when the wind magnitude is less than 5 kt. Prior to use of the thrust stand, the engineer should review NATC Instruction 10300.1 of 21 Oct 1953 to determine the instruments and cards that are required to perform a static thrust calibration. The personnel to be notified, the equipment needed and the steps to be taken are as follows:

a. Contact Flight Test Instrumentation Branch to provide, install and operate the Emery Cell (4 hr lead time).

b. Contact Boat House No. 1 or the NATC/P6M detachment to provide a line handling boat and crew necessary to pull cable from beach and secure it to the airplane, and an airplane handling boat to assist with buoy hook-up and general maneuvering (4 hr lead time).

c. Determine that cable is suitable and ready for use (3 days lead time) and that the floats on cable are ready (1 day lead time) (if new cable is required contact Carrier Suitability Branch).

d. Obtain the mobile radio communications vehicle (LSO Jeep) to provide contact between the beach and the airplane (one day lead time).

e. Secure special fitting and bridle/pendant to airplane prior to leaving the ramp to facilitate thrust cable hook-up.

f. Make provision to determine the pitch attitude (for thrust angle) of the airplane at all times during the calibration.

The maneuvering to the buoy, securing the cable, the procedure for turn-up, etc, will vary slightly with each

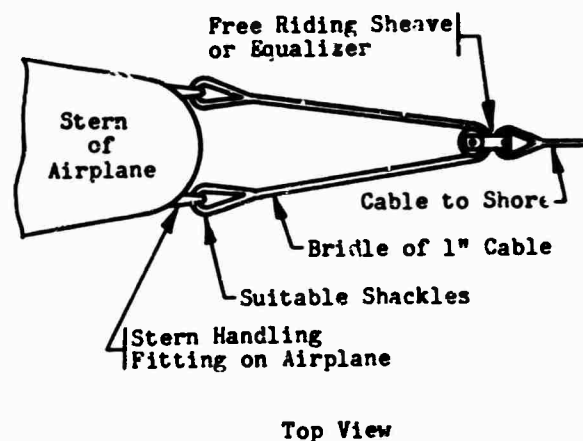


Figure 5:2  
P6M Thrust Stand Provision

airplane type. It is the responsibility of the project pilot to establish the exact procedure to be used in each case. The pilot will brief and instruct boat landing crews as necessary. The project engineer will direct the operation on the beach at the Emery Cell and be responsible for the proper calibration procedures.

### 5.3 SEAPLANE HANDLING

The lack of adequate seaplane handling facilities has been mentioned in section 1.1 as being one of the factors responsible for the slow rate of seaplane development. An improvement in seaplane handling equipment and technique would represent an important improvement in potential operating capabilities. The overall concept of water based aircraft has received a much-needed stimulus as a result of the advent of high performance seaplanes. The water based concept is a relatively broad one which includes the launching, beaching, handling, servicing and mooring. To understand the reason why seaplane handling has hampered development, one need only consider the inconveniences endured by the seaplane pilot in contra-distinction to the landplane pilot. For the landplane pilot, a relatively short taxi distance is all that lies before him after landing. For the seaplane pilot, the problem of returning to the beach can be as tiresome as the entire airborne portion of the flight. The time spent in preparing to launch, the launching itself, mooring to a buoy and the recovery up the ramp can, timewise, consume a considerable portion of the entire operation. Wind and weather intensify these problems. Mooring buoys have been inadequate to the extent that a portion of the crew has to stay aboard the seaplane while moored in the water.

Many developments in the seaplane water based concept have at one time or another been proved in small operations. In WW II a PBM seaplane detachment showed that advance base operations could be sustained over a surprisingly long period of time, during which time the seaplane was never beached. Operations with submarines have been successfully demonstrated. Refueling missions between submarines and the current P5M's have been successful. The use of portable and inflatable U-docks for minor repairs and maintenance has also been demonstrated. It remains to be illustrated that by the routine employment of these developments the capabilities of the seaplane can be expanded under the water based concept.

For years, the standard methods of moving seaplanes on the ramp and in and out of the water has been by the use of beaching gear. The three-unit gear consists of two main mounts and a tail mount. The gear is equipped with adequate flotation means and hand brakes. Since the gear is continually immersed in the water during operations, it is subject to a considerable amount of corrosion on exposed parts despite its relatively simple construction. When using beaching gear, one end of a line is attached to the tail and the other end is attached to a tractor. The bow (either left or right side) is attached

by a "lizzard" to a buoy which is in turn attached to an "in-haul, out-haul" line. This type of launching system is fairly standard and is illustrated in figure 5:3.

Handling provisions for ski-equipped seaplanes depend on the method of ski attachment. A PBM equipped with a non-flush mounted ski used beaching gear modified by the addition of 2 inch thick metal plates on the side mounts and a stilt arrangement on the tail mount. The single ski JRF also employed a stilt arrangement for side-mounted beaching wheels. A twin ski JRF contained wheels within each ski. The Convair F2Y incorporated rollers on the trailing end of the ski and a small wheel on the aft fuselage. Amphibious seaplanes have made use of their retractable wheels to provide entrance to and egress from the water. The operation of landing gear in water introduces several design restrictions. One design for a high performance ski-equipped plane employed retractable wheels which could be used only during beaching and launching operations.

A satisfactory handling system for high performance seaplanes has been the subject of a good deal of research. The use of a cradle for launching and beaching was processed by the Germans on such seaplanes as the "Blohm and Voss" and the "Dornier". Application of the use of cradles was fairly limited in the United States (prior to WW II) to the "Boeing Clipper". Since that time many designs have been proposed but few have been built. A review of previous designs indicates that many ingenious devices were proposed which had as their basis the reduction of time and manpower required to accomplish the beaching, the ability to operate under a variety of weather conditions and the applicability of the cradle to all types of seaplanes ( a universal cradle).

In seaplane cradle design the first consideration is the positioning of the seaplane within the cradle. Another design consideration is the locomotion and control of the cradle on the ground and in the water with and without the seaplane engaged. Lastly, the flotation control of the cradle must be adequate. In full scale handling operation during the positioning phase, suitable bumpers and rollers are installed on the cradle to prevent damage to the seaplane hull. Provisions are also installed to submerge the cradle in order to position the seaplane. When the plane is properly positioned, the cradle is raised to provide a tight fit between cradle and seaplane with no relative motion. The ultimate in cradle development is, of course, one that is self propelled and not dependent on auxiliary craft to maneuver the cradle into position.





The R3Y was the first large modern seaplane to use a cradle which is manned and maneuvered into a mating position by small boats. Mating of the seaplane with the cradle is aided by the high degree of maneuverability of the R3Y with its smooth-acting reverse pitch turbo-prop engines. When the cradle has been fastened to the seaplane, maneuvering and motion up the ramp is accomplished by the use of the seaplane's engines. The positioning of the plane in the cradle is sometimes made difficult under conditions of adverse wind and wave. The beaching vehicle for the P6M incorporates an additional positioning feature which consists of a differential run-out cable. As the seaplane enters the cradle, a hook on the keel of the seaplane engages the run-out cable which functions to ensure that the seaplane is correctly positioned in the cradle.

The concept of a true water-based seaplane has produced some unique problems. In this concept the seaplane is assumed to spend much of its time in the water thus requiring only infrequent beaching operations for major repair. Minor repair is accomplished from portable U-docks installed and transported by surface units. The modification of several seaplane tenders is planned in order to carry out the surface support ship program. In line with these developments a new type of mooring buoy will no longer require a crew to remain aboard the seaplane at all times.

During the testing of large high performance seaplanes answers to the following questions will indicate the suitability of beaching and launching equipment:

- a. Is the plane completely controllable up to the final approach to the cradle?
- b. What are the limiting weather conditions for successful mating of cradle and plane?
- c. What are the limiting or suggested engaging speeds and angle of entry?
- d. How much sea-room is required to accomplish the mating?
- e. What is the ease of maneuvering of the seaplane with the beaching cradle attached?
- f. What are the difficulties in positioning the cradle prior to mating?

g. Must personnel remain on the cradle at all times and how are the beaching cradle controls operated?

h. How do the plug-in controls function for communication, pilot-operated brakes or steering?

In the programming phase, all the handling requirements of the seaplane must be reviewed to ascertain that the requirements can be met. The strength of the aprons and ramps can be obtained from Public Works as well as the hangar size that will have to accommodate the plane. Equipment such as handling boats and emergency equipment must be available in order that the testing schedule will not be jeopardized. The size and depth of the areas where the plane will be maneuvered and moored must be known.

In the case of the P6M preliminary space requirements were obtained from the use of scale outlines of both the plane, hangar area and operating water basins. Depending on wind and wave conditions approach paths can be planned based on preliminary estimates of turning behavior. Since these are only estimates adequate margins of safety must be planned.

#### 5.4 FUTURE DEVELOPMENTS

The problems of high performance seaplanes are numerous, unique and imposing, but not to any large degree impossible of solution. The operation of seaplanes with compatible aerodynamic and hydrodynamic characteristics up to speeds of Mach 3 are considered feasible. Advance designs of these high speed seaplanes have already been tested in model towing tanks by such agencies as the National Advisory Committee for Aeronautics.

The characteristics of future seaplanes will be highly dependent on the mission and type of operation planned. Several features have, in the course of testing, indicated their adaptability to seaplanes. Some of these features are:

- a. Delta-wings for high trim angles while maintaining controllability.
- b. Boundary layer control-high lift for lower landing speeds.
- c. Tilting wings for high wing lift while maintaining satisfactory hull trims.
- d. Development of hydro-skis and hydro-foils or combinations thereof.
- e. Development of STOL and VTOL aircraft with water-based potentialities.

These features do not exhaust the list of potential improvements for future seaplanes. The development of the high length-beam ratio hulls, with relatively clean aerodynamic characteristics, has made possible high performance seaplanes. Studies have been made concerning the type of seaplane configuration best suited to the mission. Based on some of these studies, it appears that hull types are best suited for heavy patrol seaplanes, hydro-skis for high performance fighter aircraft and either hulls or skis for high performance medium weight bomber-patrol seaplanes. This is by no means a rigid classification and may well be modified by future development.

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